



Emerging granularity and the anomalous Hall insulator in disorder-tuned magnetic films

(Nonconventional Insulators in Disordered Magnetic Systems)

A. F. Hebard (University of Florida, Gainesville, FL)

P. Mitra, R. Misra, S. Ghosh

K. Muttalib (UF) & P. Wölfle (Karlsruhe)

Research supported by NSF





FM in 2D: Motivating Questions.

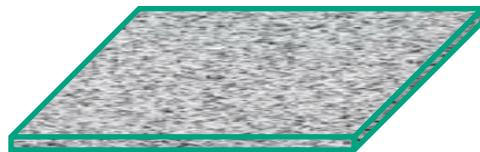
1. Band ferromagnetism relies on itinerant electrons. When itinerancy is compromised by disorder, what happens?
2. Any signatures at $\hbar/e^2 = 4100 \Omega$?
3. Is there a ferromagnetic M-I transition?
4. Ferromagnetic behavior and film morphology?
5. Nonconventional magnetic insulators?

Magnetic Insulators

Local moment? Localized charge? FM, AFM, glass?
Lowest energy state? Spin waves? New phases?
Long range order? T_c ?

(I)

SAF state (dipole-dipole)
Anomalous Hall insulator



Emergent granularity

(II)

Emergent granularity

Power-law behavior &
M-I transition

(III)

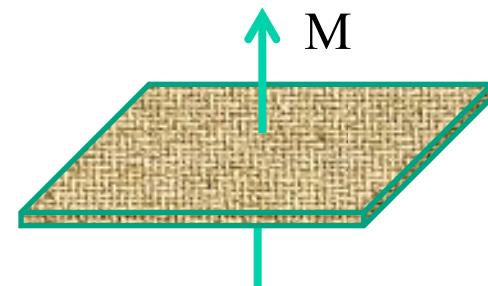


Curie temperature
(T_c) suppression

Disorder strength (decreasing itinerancy)

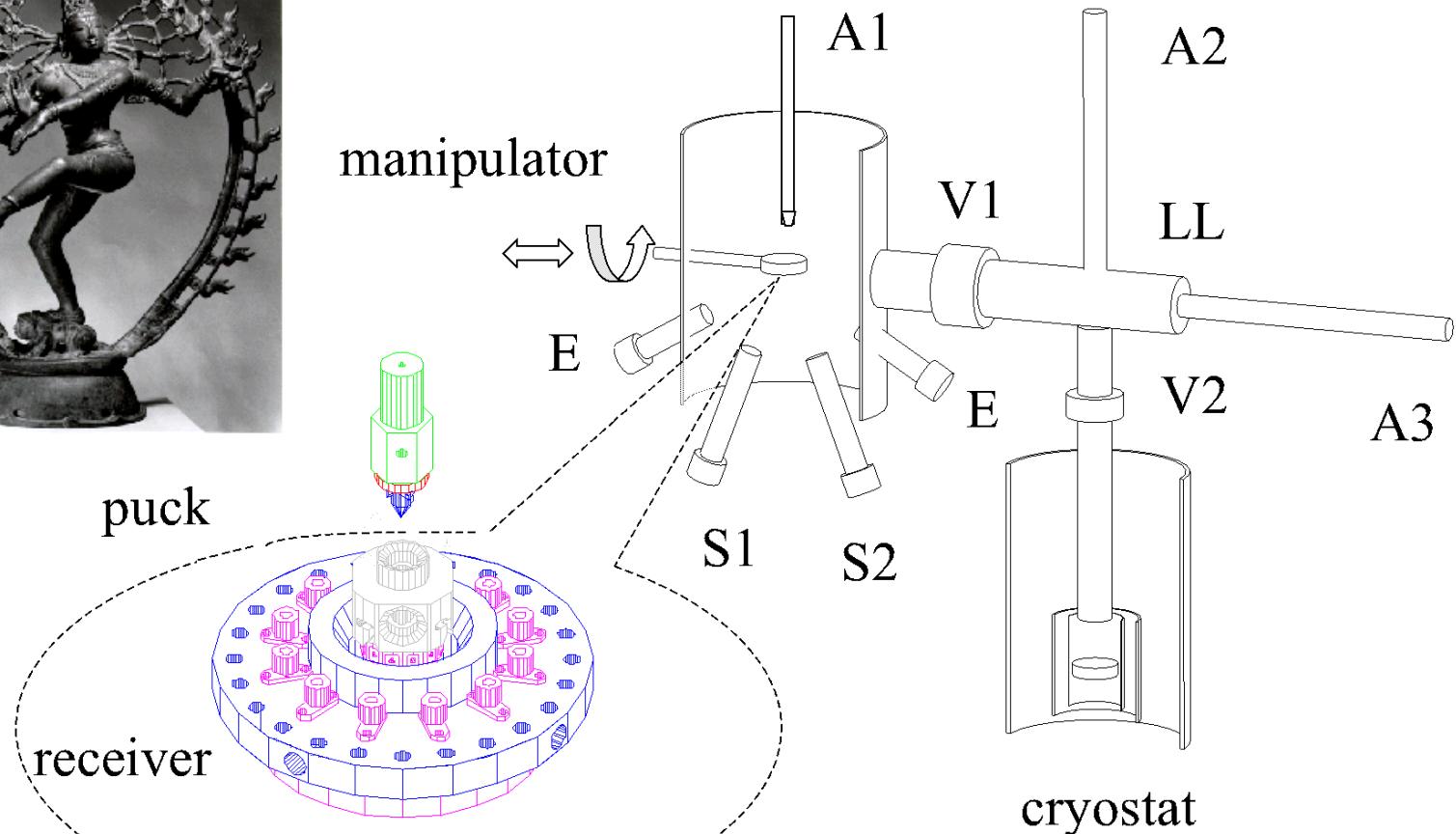
Quantum corrections to the conductivity in two dimensions

Polycrystalline magnetic thin films
(itinerant versus local moments)





SHIVA- Sample Handling In VAcuum





PART (I)

Polycrystalline Fe: weak disorder

*Evidence for a
disorder-dependent localization correction to the
anomalous Hall (AH) conductance of
Fe thin films*

P. Mitra, et al, PRL **99**, 046804 (2007)



Prelude (some background)

At low temperatures,

$$\sigma_{2D} = \sigma_{Drude} + \Delta\sigma_{WL} + \Delta\sigma_{e-e}$$

Disorder:-

Lattice imperfections, grain boundaries, etc

Which of the processes (WL or e-e interaction) is dominant at different disorder strength?

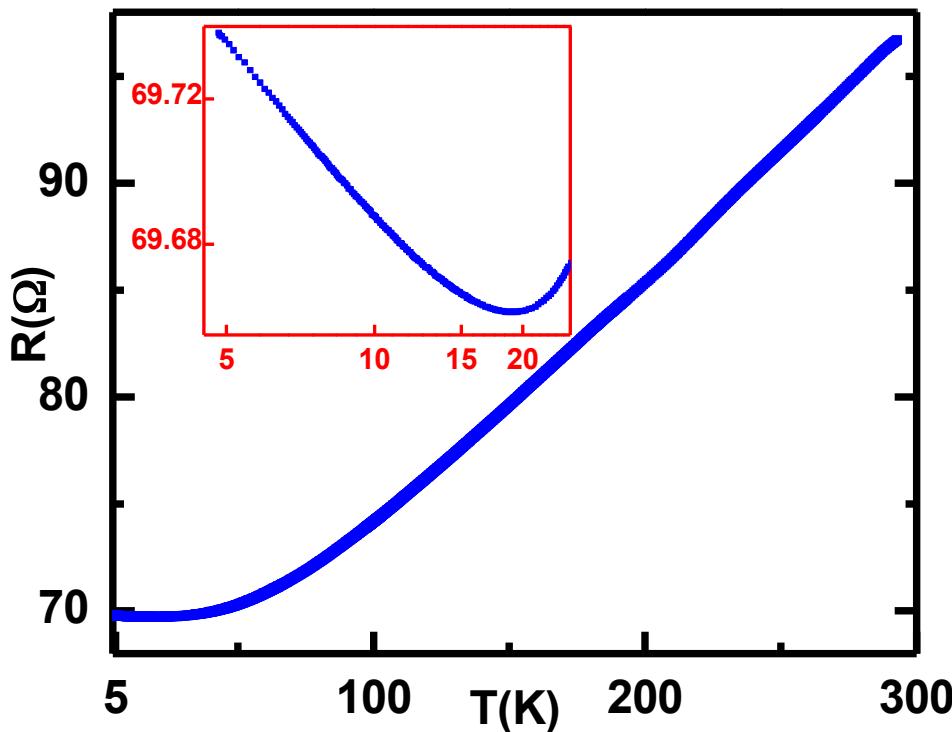
Quantum corrections are affected by spin alignment (ferromagnetic order).



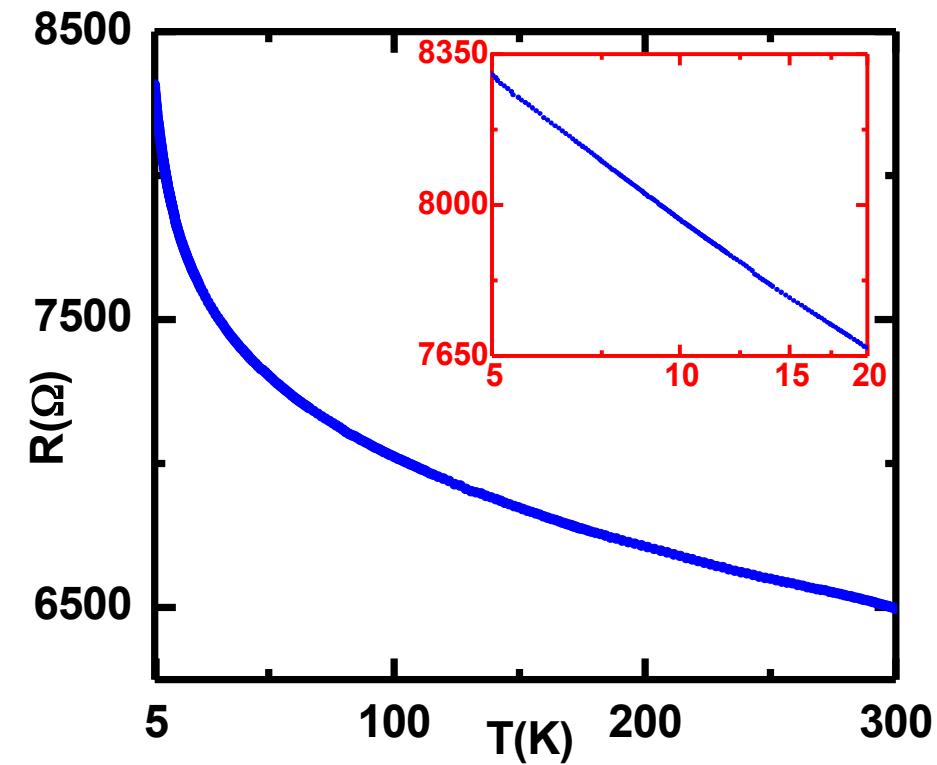
Weak disorder: Fe on glass substrates

Magnetron sputtering at room T

$d=100\text{\AA}$, $R_0=70\Omega$



$d=20\text{\AA}$, $R_0=8300\Omega$



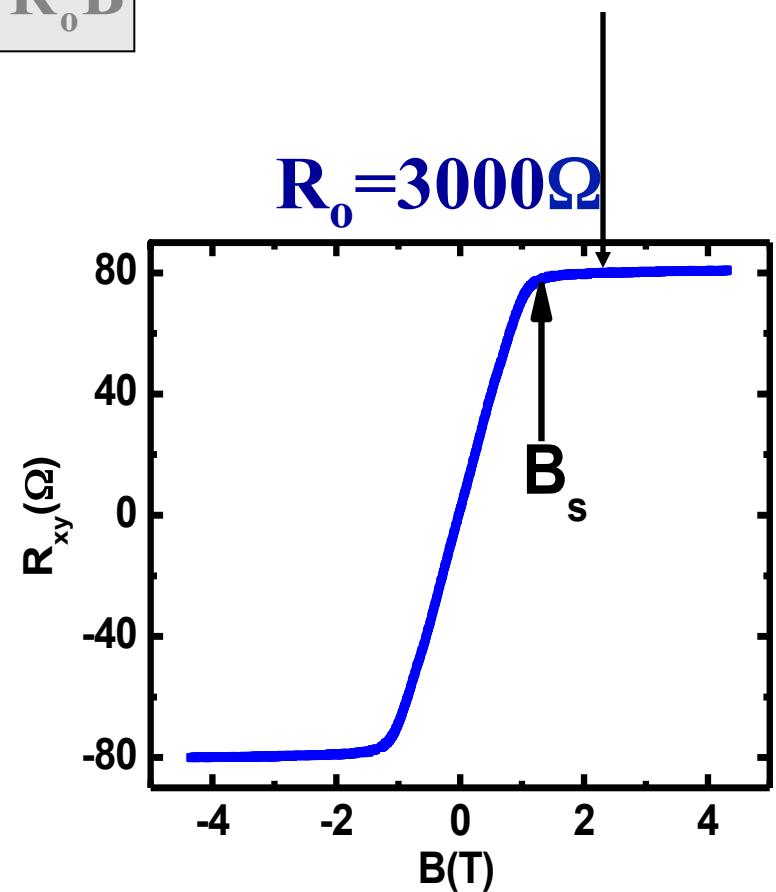
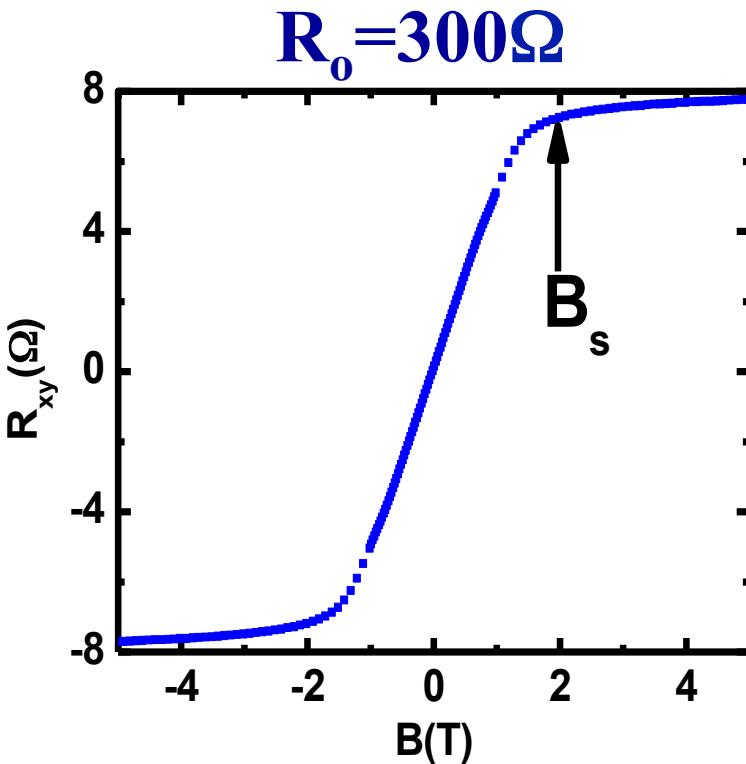
Inset: Log(T) dependence of R_{sq} at low temperature



Anomalous Hall effect in iron

$$R_{xy} = \mu_o R_s M + R_o B$$

Remember this value !



Note: decrease in B_s and increase in R_{xy} with R_o



Weak localization

Magnetic Field

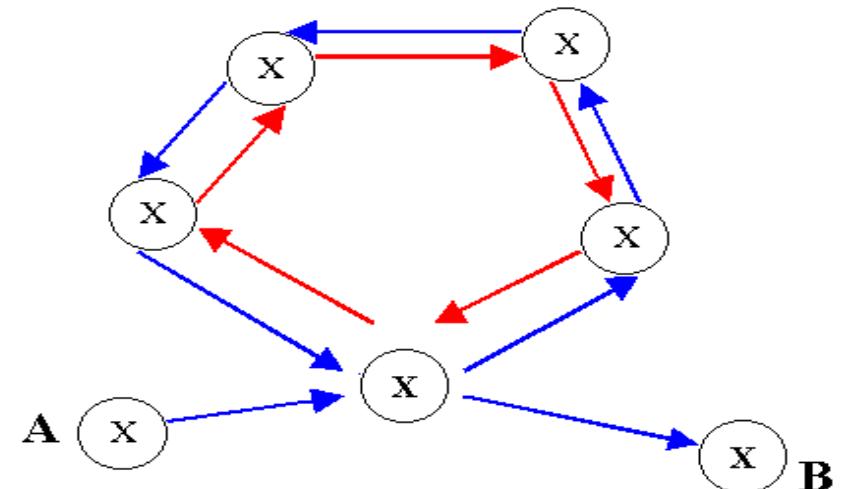
$$\vec{p} \rightarrow \vec{p} - \frac{e}{c} \vec{A}$$

$$\Delta\varphi_H = \frac{2e}{c\hbar} \oint \vec{A} \cdot d\vec{l} = 2\pi \frac{\Phi}{\Phi_0}$$

$$\sigma(H) - \sigma(0) \sim \frac{e^2}{\hbar} \ln\left(\frac{eHD\tau_\varphi}{\hbar c}\right)$$

Negative magnetoresistance

Magnetic field suppresses coherent backscattering



A necessary condition for localization,

$$\max \{\tau_s^{-1}, \tau_{so}^{-1}, \omega_c\} \ll \tau_\varphi^{-1} \ll \tau_{tr}^{-1}$$

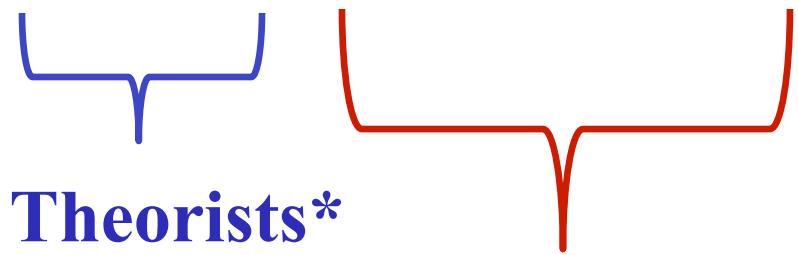
$\tau_\varphi^{-1} \sim T$ in FM films due to spin conserving inelastic scattering off of spin wave excitations!



Relative resistance/conductance changes

Experimentally, $R_{xx}^{AH} \gg R_{xy}^{AH}$

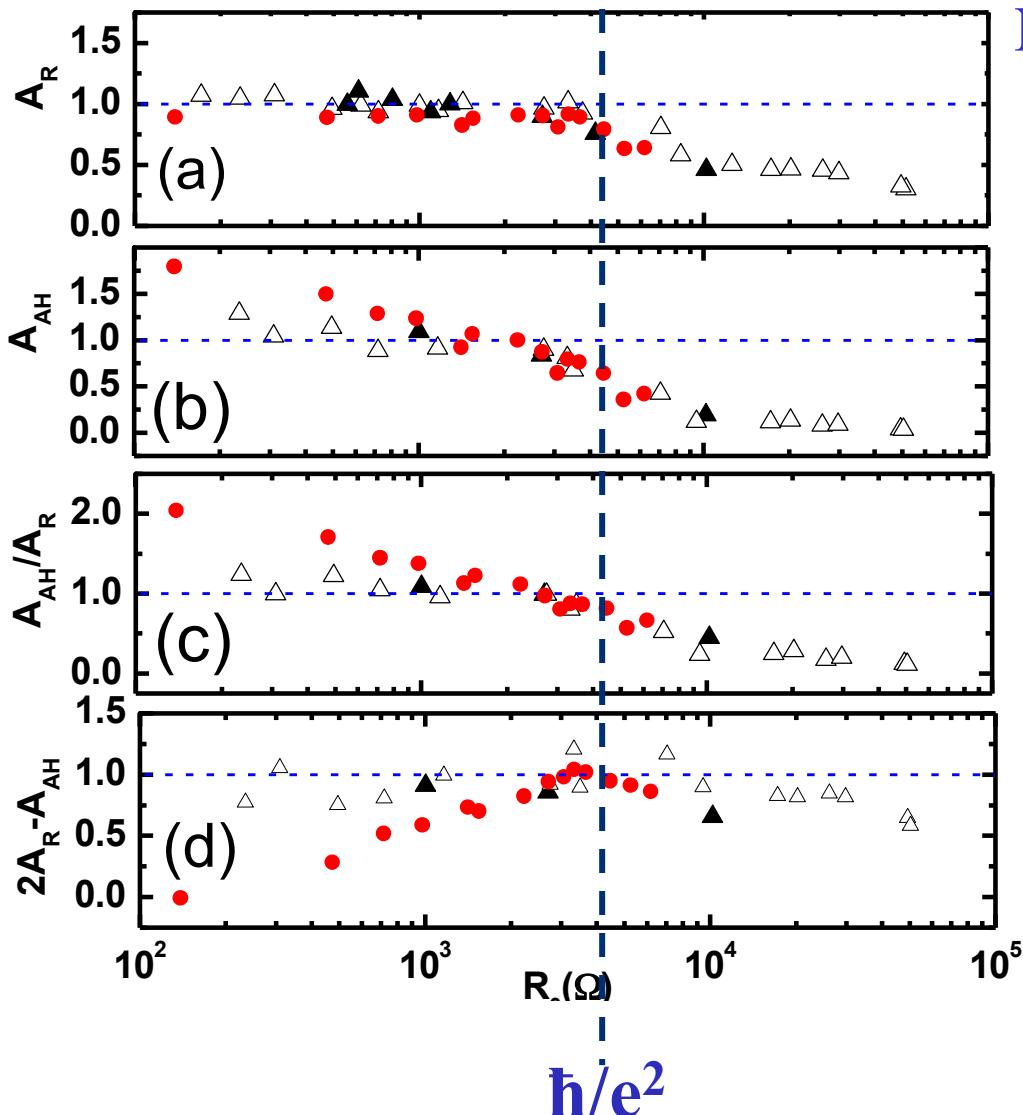
$$\sigma_{xy}^{AH} \approx \frac{R_{xy}^{AH}}{(R_{xx}^{AH})^2} \quad \Rightarrow \quad \frac{\delta\sigma_{xy}^{AH}}{\sigma_{xy}^{AH}} = \frac{\delta R_{xy}^{AH}}{R_{xy}^{AH}} - 2 \frac{\delta R_{xx}^{AH}}{R_{xx}^{AH}}$$



*No conductivity corrections to AH from e-e interactions
(Wölfle, et al) or from WL side-jump (Dugaev et al)!



A_R and A_{AH} for Fe films on glass (triangles) and sapphire (circles) substrates



Note sensitivity to substrate!

$$\Delta^N \sigma_{xx}^{WL} = \ln(T/T_0)$$

$$\Delta^N \sigma_{xy}^{WL} = \frac{\sigma_{xy}^{SSM} \ln(T/T_0)}{(\sigma_{xy}^{SSM} + \sigma_{xy}^{SJM})}$$

A weak localization correction within the skew scattering model is present in Fe films !



PART (II)

Polycrystalline Gd: weak disorder

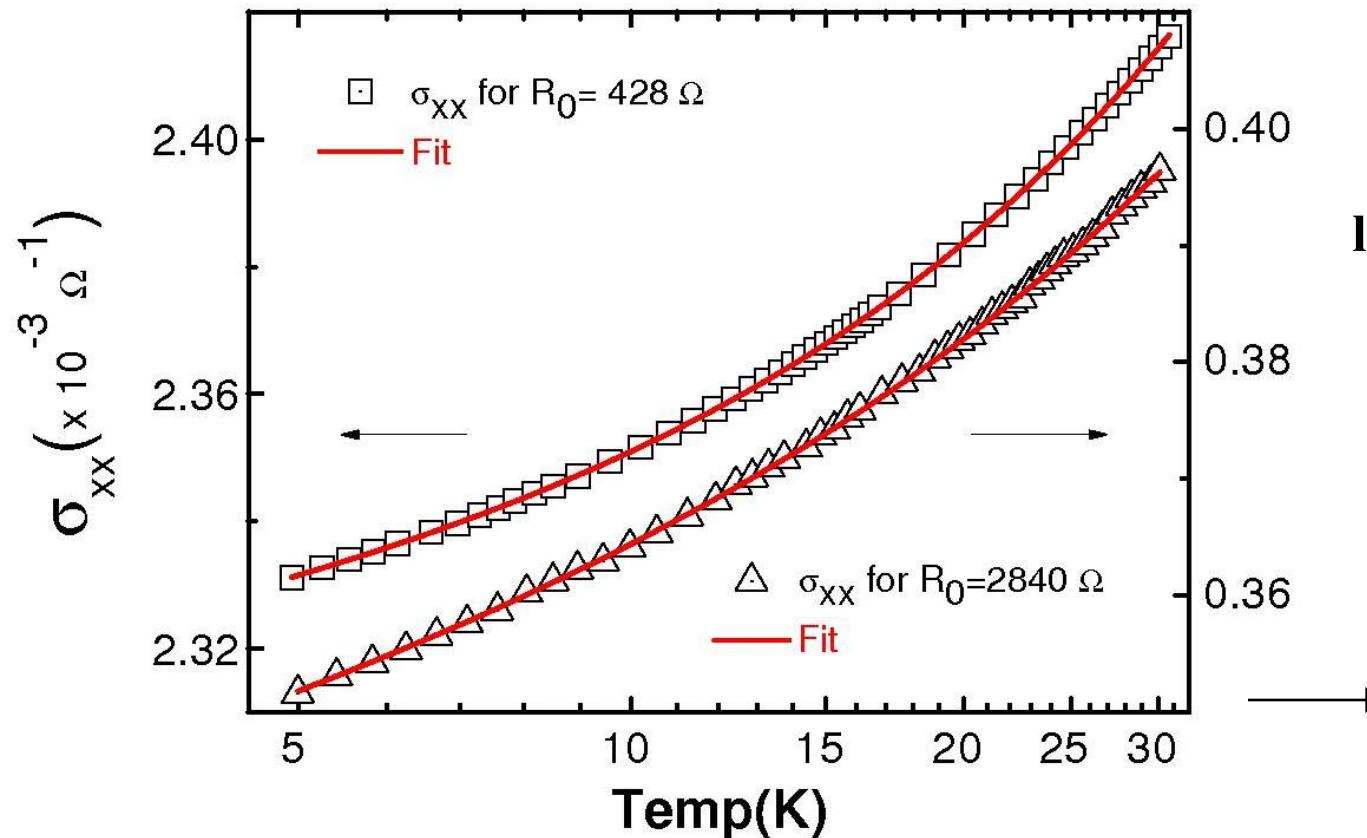
Given the importance of spin waves in Fe films, one might expect to observe even larger effects in FM films such as Gd (a local moment system) which has larger and more strongly coupled magnetic moments.

Spin-wave mediated quantum corrections to the conductivity in thin ferromagnetic gadolinium films



Quantum corrections to Conductivity ($H = 0$)

Misra et al., Phys. Rev. B79, 140408(R) 2009



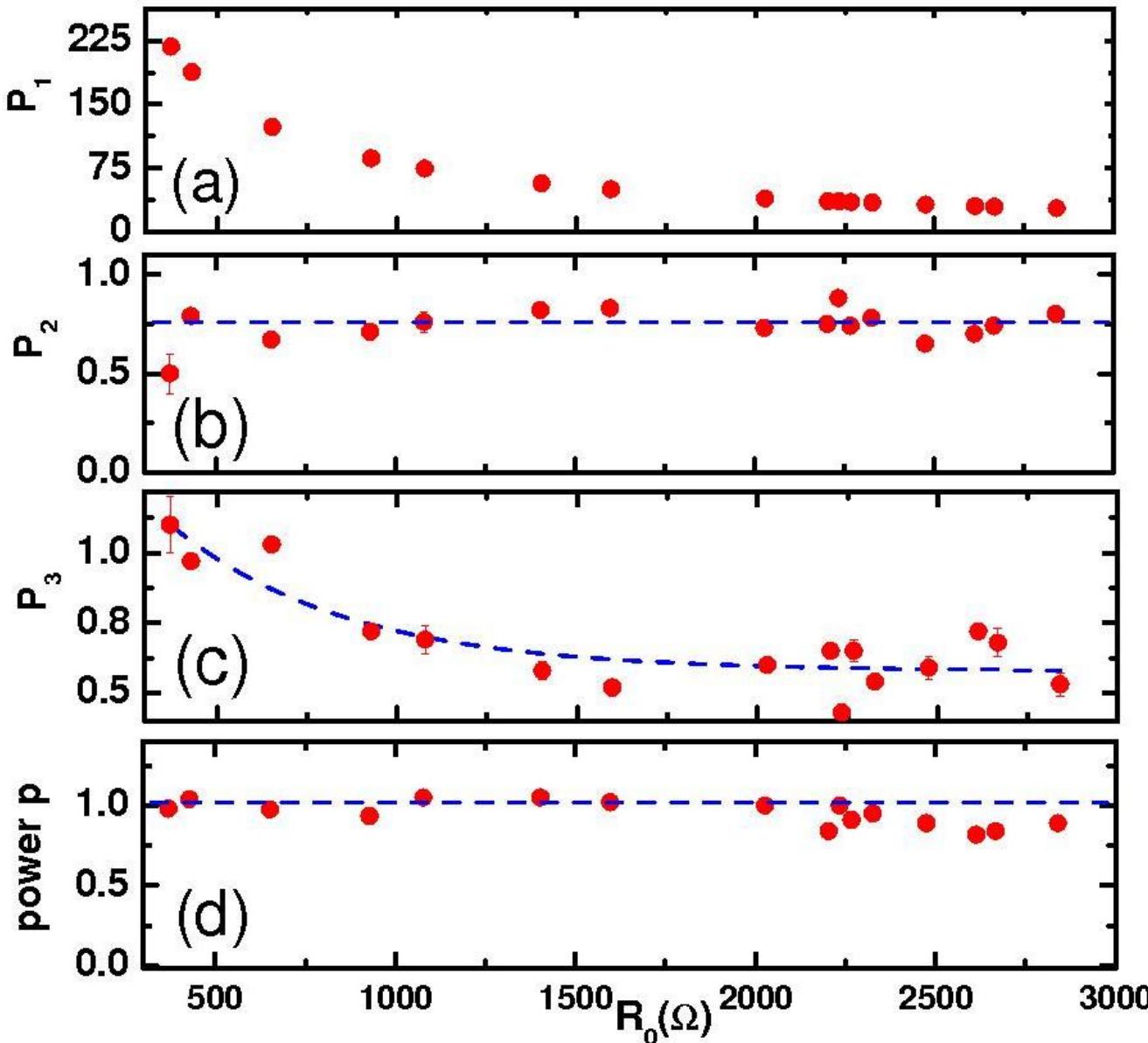
Note logarithmic and linear corrections to the conductivity!

Fitting function :

$$\frac{\sigma_{xx}}{L_{00}} = P_1 + P_2 \ln\left(\frac{T}{T_0}\right) + P_3\left(\frac{T}{T_0}\right)^P$$



Dependence of fitting parameters on disorder parameter R_0 of Gd films



16 films

Fitting Equation :

$$\frac{\sigma_{xx}}{L_{00}} =$$

$$P_1 + P_2 \ln\left(\frac{T}{T_0}\right) + P_3\left(\frac{T}{T_0}\right)^P$$

A linear-in-T
localizing quantum
correction to the
conductivity !



Spin wave mediated Altshuler-Aronov corrections to conductivity

The total spin wave contribution

$$\frac{\delta\sigma_{xx}}{L_{00}} \approx \left(\frac{Jk_F^2}{2\pi B} \right)^2 (\varepsilon_F \tau) \frac{T}{Ak_F^2}$$

- The disorder dependence of the linear T contribution is given by $P_3 \propto \varepsilon_F \tau$, which decreases with increasing disorder.
- Experimentally, P_3 does indeed decrease with disorder up to $R_0 \approx 2000\Omega$ and then saturates.
- A localizing linear-in-T quantum correction to the conductivity.

* Misra et al. Phys. Rev. B79, 140408(R) 2009



PART (III)

Polycrystalline Fe: strong disorder

(Beyond the region of quantum corrections)

The Anomalous Hall Insulator

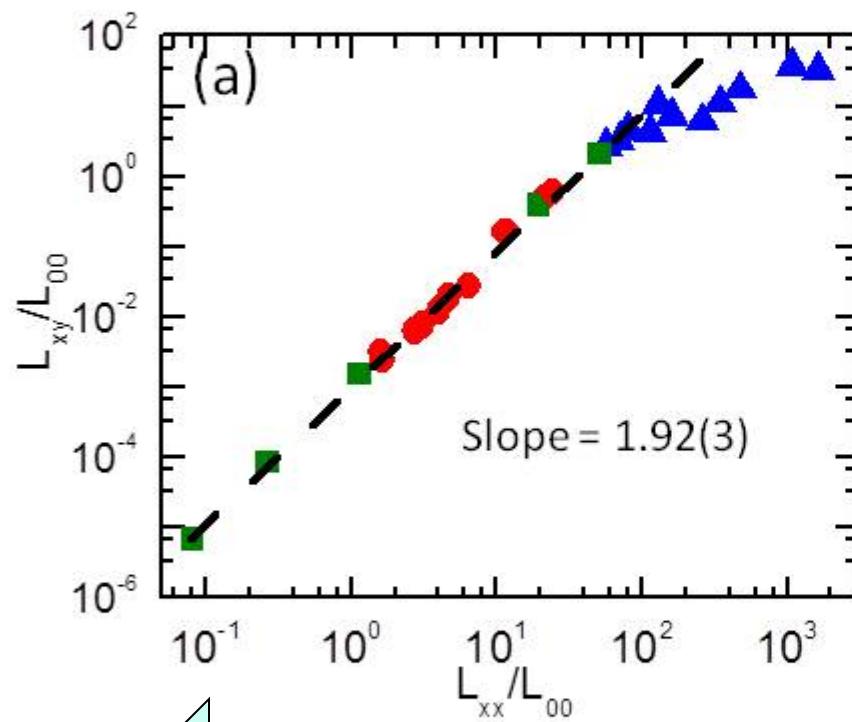
(AHI)

(A nonconventional insulator ?)

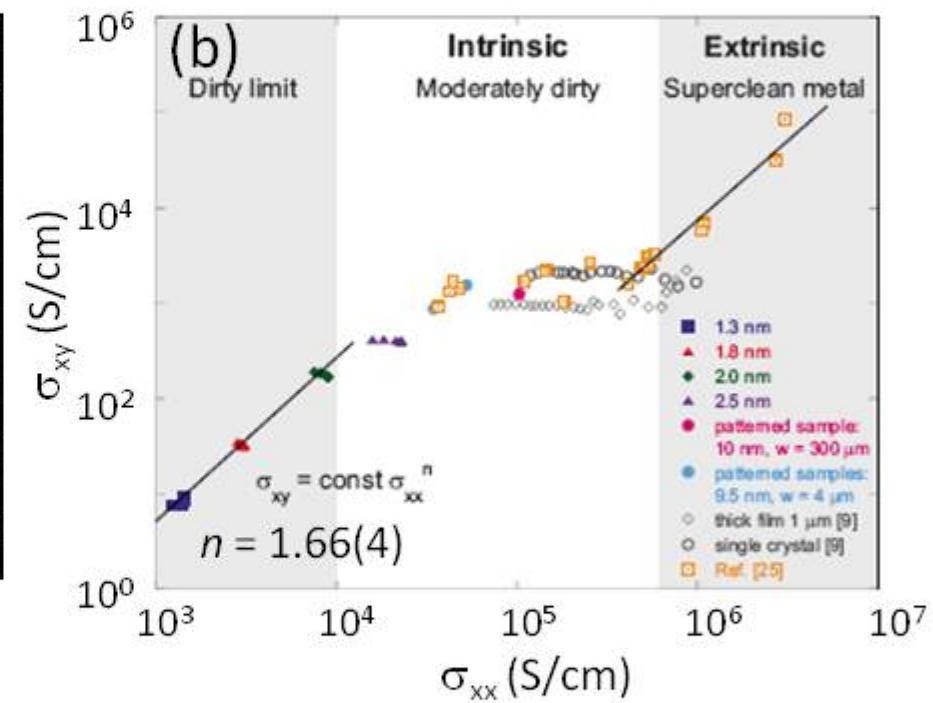


Logarithmic plots of AH conductivity vs longitudinal conductivity show power-law behavior

2D sputter-deposited Fe/glass



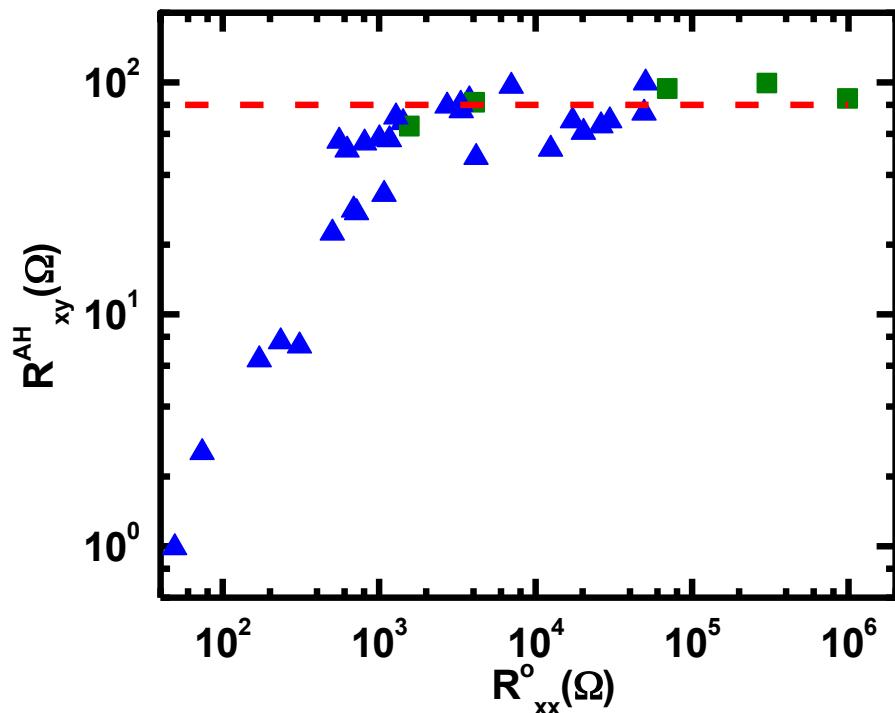
3D pulsed-laser deposited epitaxial Fe(001)/MgO



Increasing disorder strength

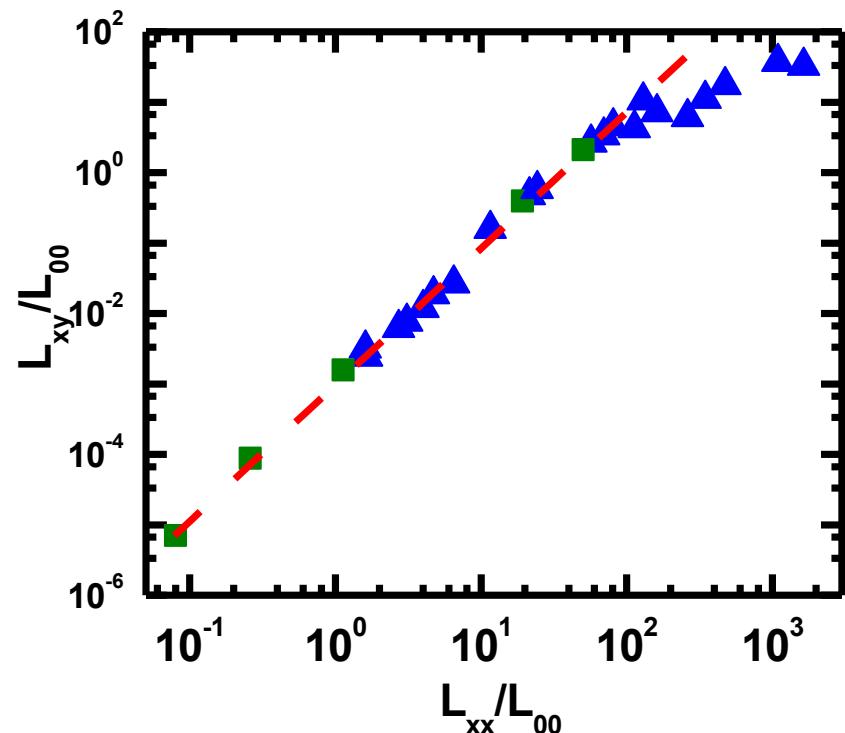


Anomalous Hall Insulator



Blue points iron

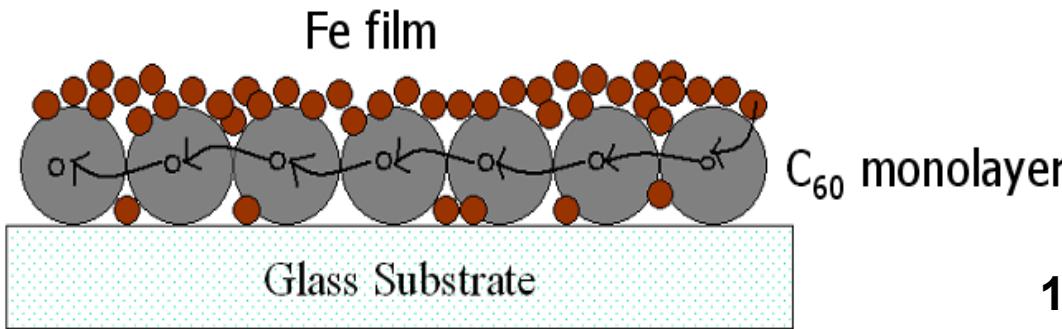
Green points Fe/C₆₀ samples



$$\begin{aligned}L_{xx} &\rightarrow 0, L_{xy} \rightarrow 0 \\L_{xy} &\propto L_{xx}^2 \\R_{xy} &= \frac{L_{xy}}{L_{xx}^2} \approx 70\Omega\end{aligned}$$

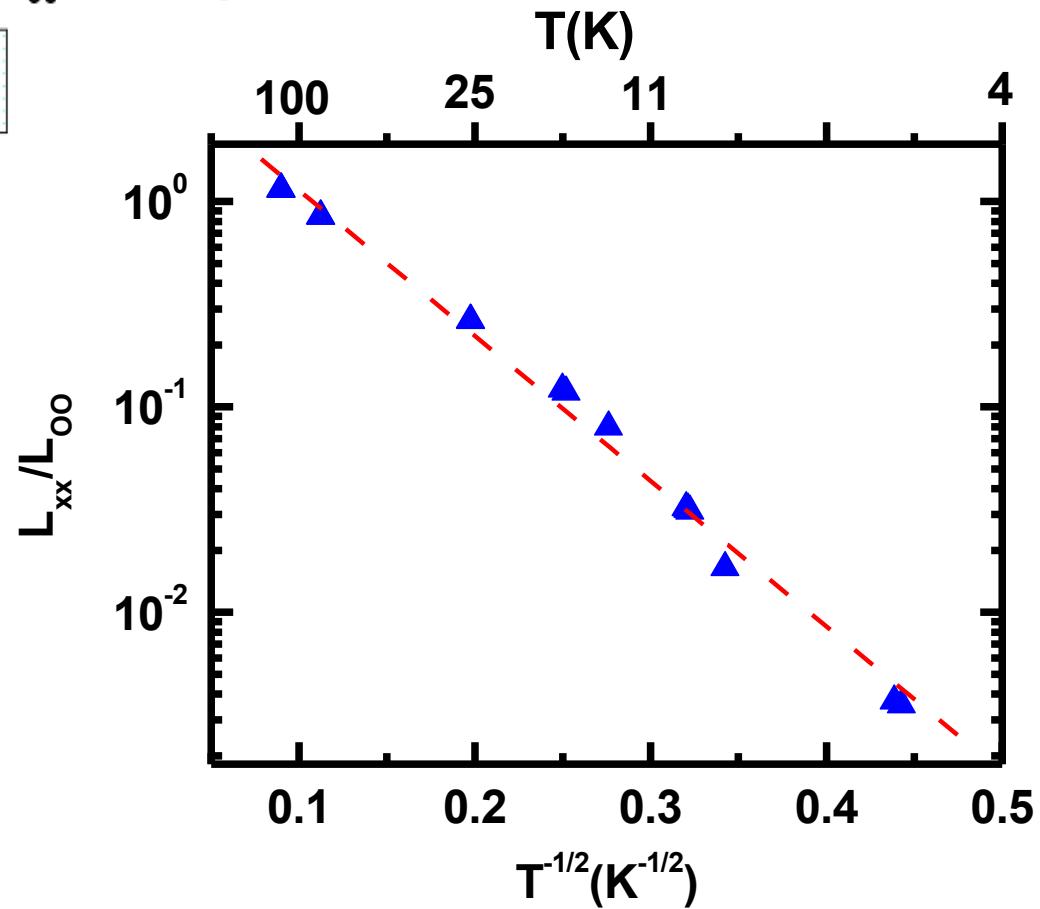


Strong disorder:Fe-C₆₀ (e-e mediated hopping conductivity)



$$L_{xx}(T) = L_{xx}^0 \exp\left(-\left(\frac{T_\xi}{T}\right)^{1/2}\right)$$

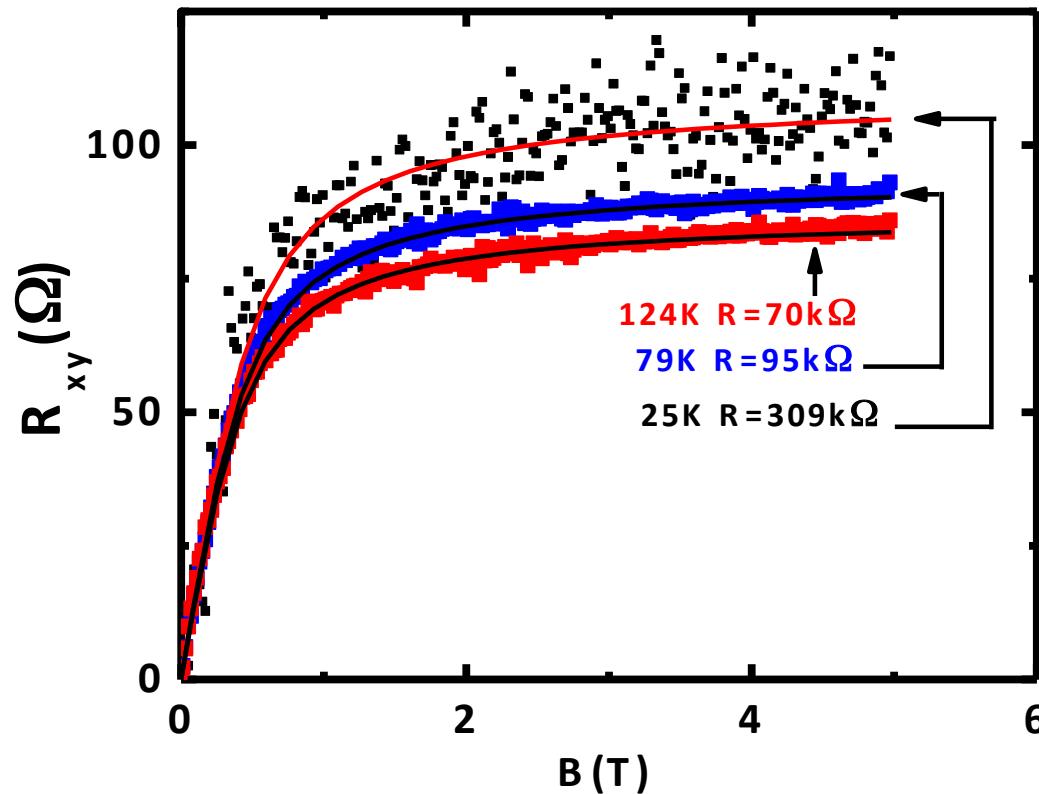
$$T_\xi \sim E_c \sim \frac{e^2}{\langle d \rangle} = 266 \text{ K}$$





AH effect in Fe/C₆₀

$$R_{xy}^{AH}(T, B) = R_s(T)M(T, B) = R_{xy}^0(T)\left(\coth(P_1(T)B) - \frac{1}{P_1(T)B}\right)$$



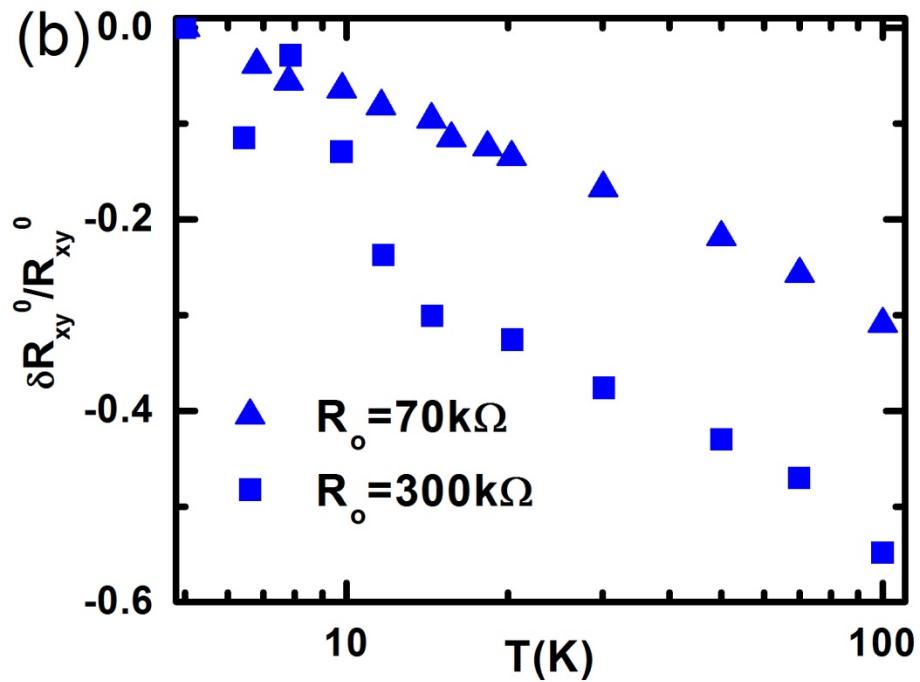
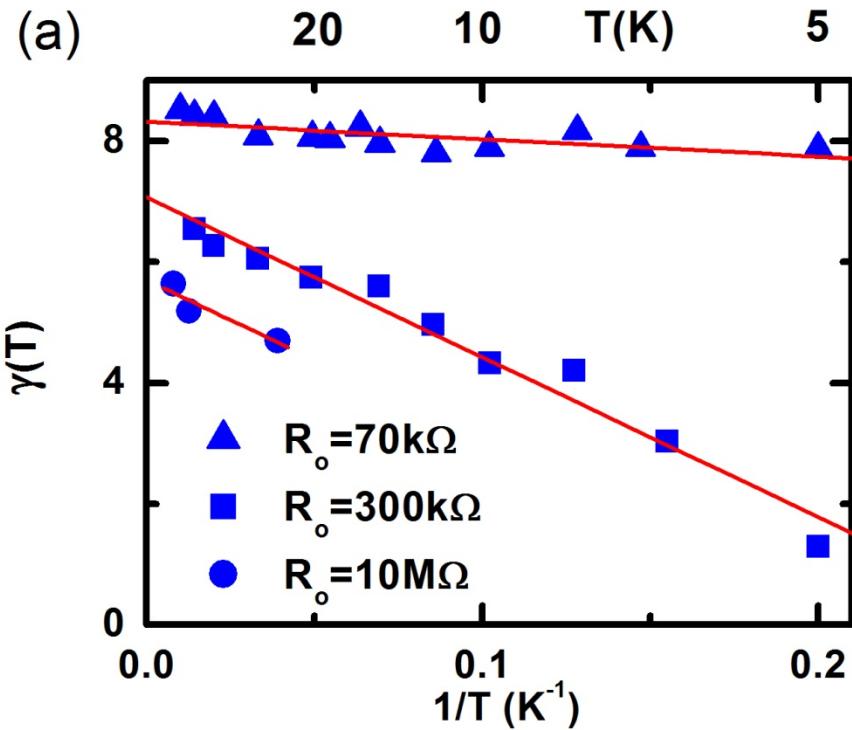
Solid lines represent fits to the Langevin function



AH effect is dominated by intragranular scattering

Magnetization in a superparamagnetic system (3 films)

$$M(B, T) = M_s L (\mu B / k_B T)$$

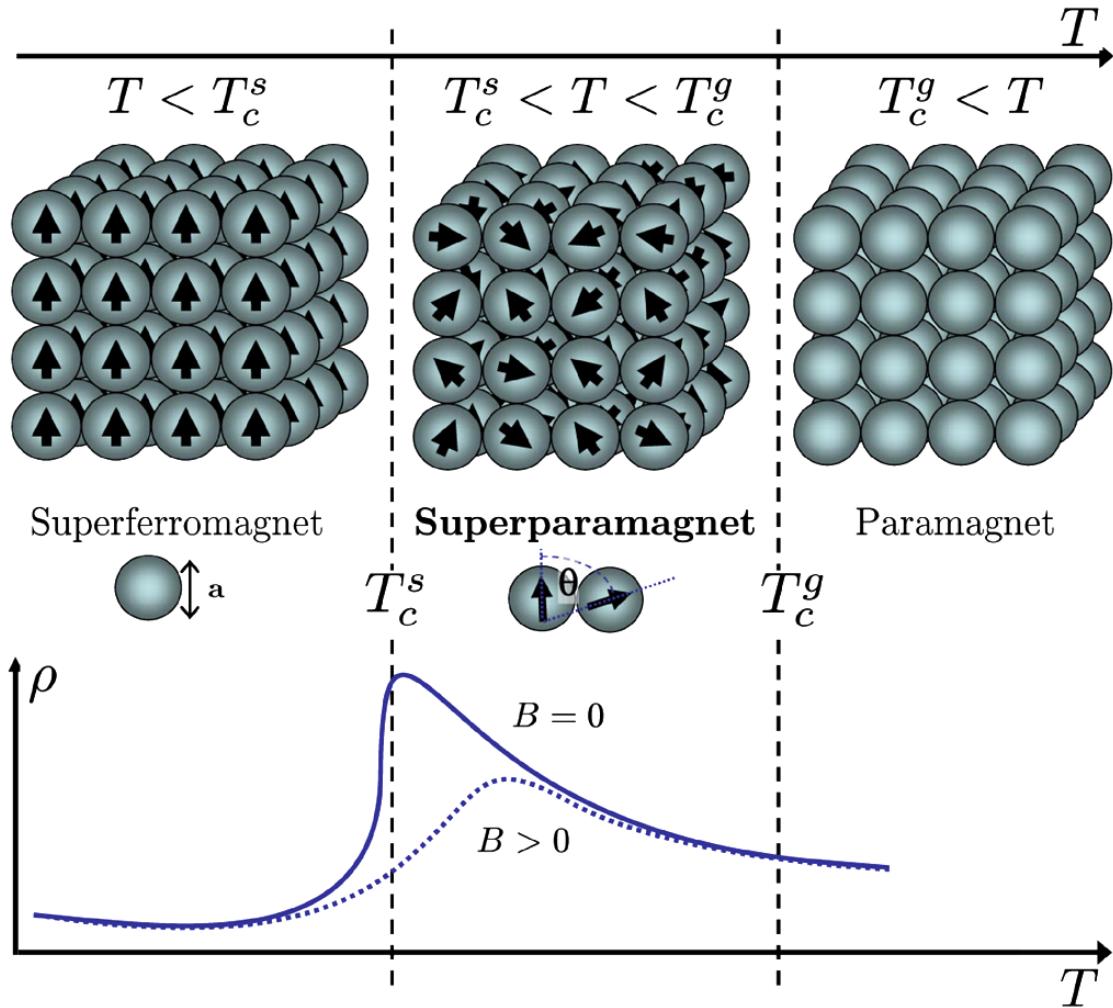


$$R_{xy}^{AH}(T, B) = R_s(T)M(T, B) = R_{xy}^0(T)(\coth(\gamma(T)B) - 1/\gamma(T)B)$$



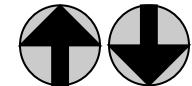
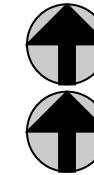
“Electron Transport in Nanogranular FMs”

I. S. Beloborodov et al., PRL 99, 066602 (2007)



T_c^s = macroscopic
Curie temperature
 T_c^g = single grain
Curie temperature

SFM state from
dipole interactions



SAFM state in 2D?



Two particle dipole-dipole interaction*

$$T_g = \frac{\mu_0 M^2}{4\pi k_B d^3} , \text{ where } M = M_s V$$

$$= 12 \text{ K for } d = 10 \text{ Angstrom}$$



*T. Jonsson et al., Phys. Rev Lett. 75, 4138 (1995)



PART (IV)

Polycrystalline Gd: strong disorder

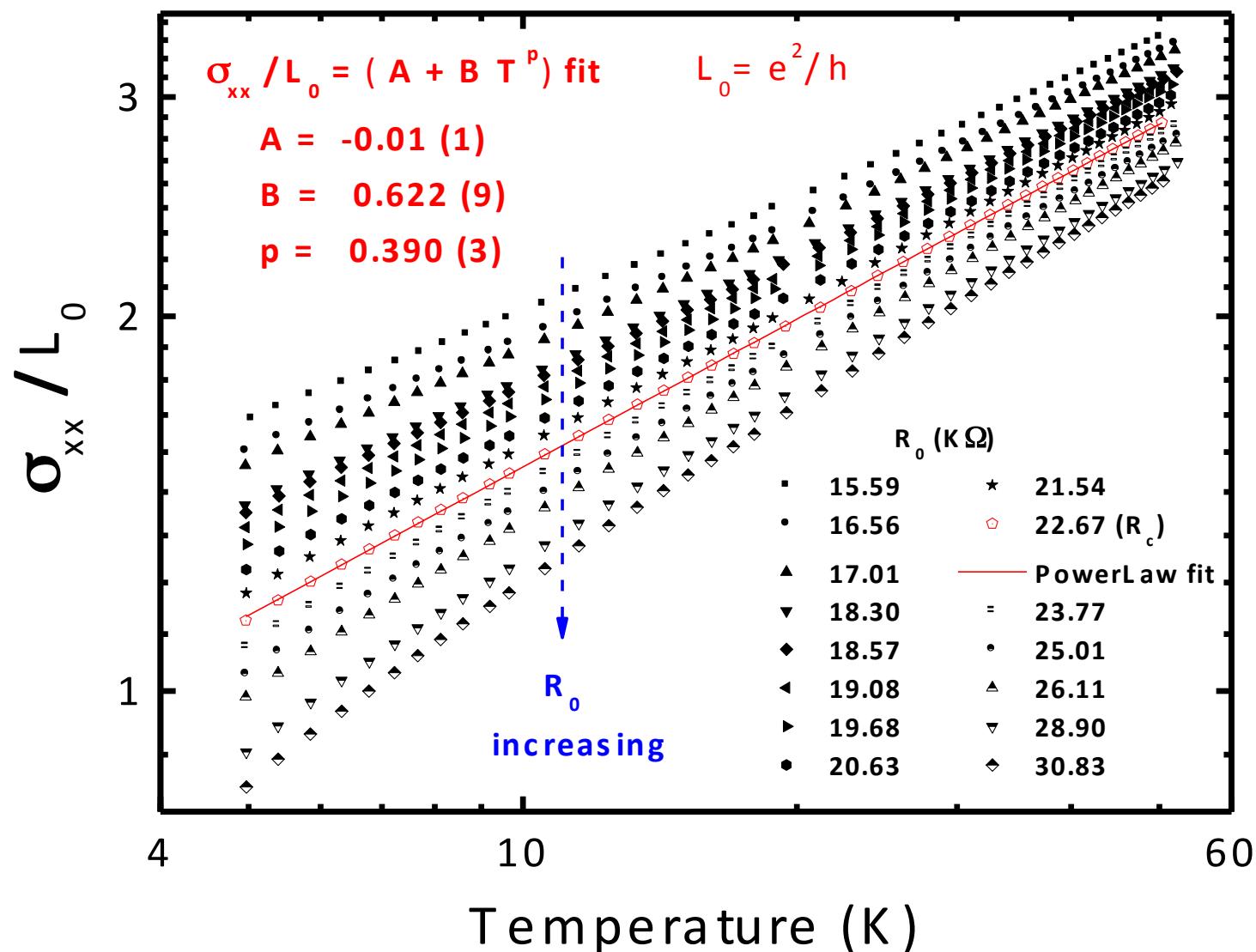
(Beyond the region of quantum corrections)

*Finite temperature critical behavior
near the Anderson quantum phase
transition*

An oxymoron? (“a seemingly self-contradictory effect”)

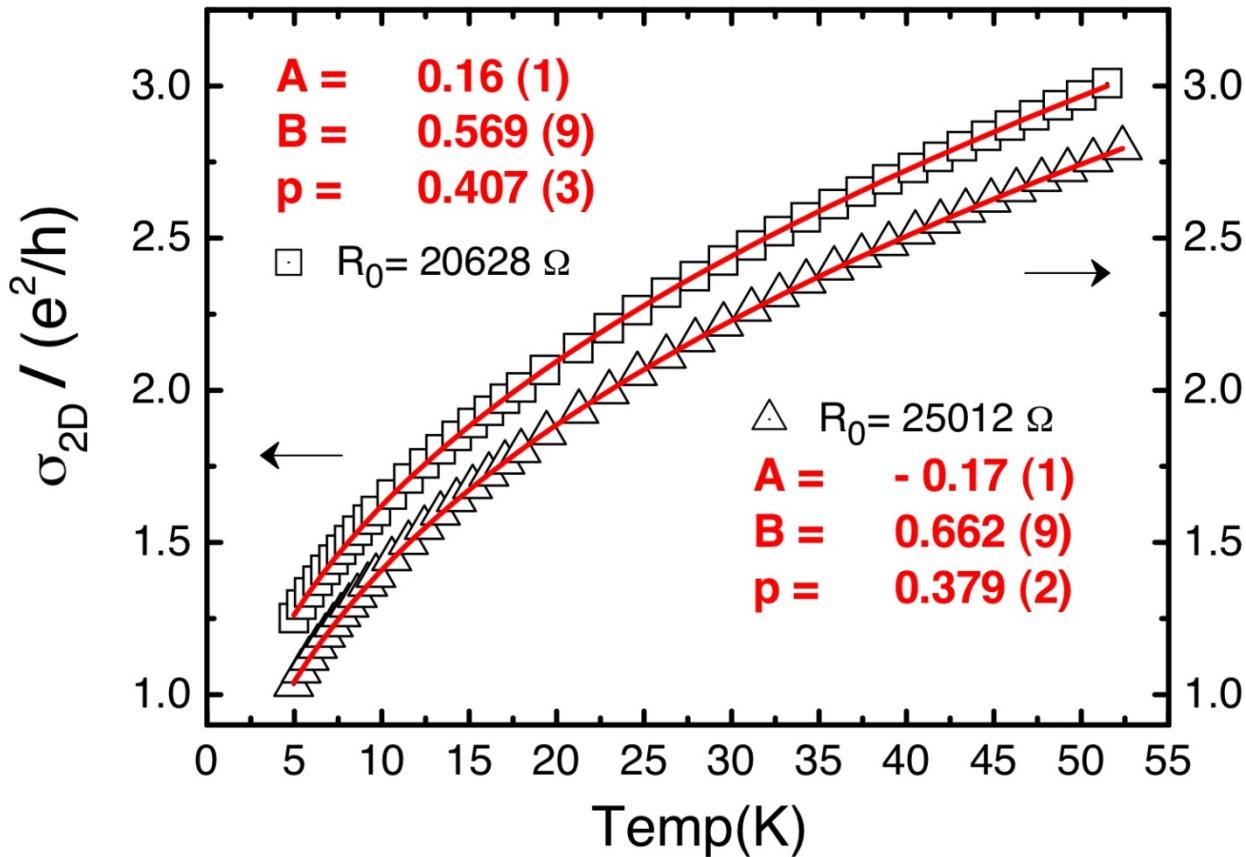


Single film annealed: 16 stages





Two samples straddling critical disorder

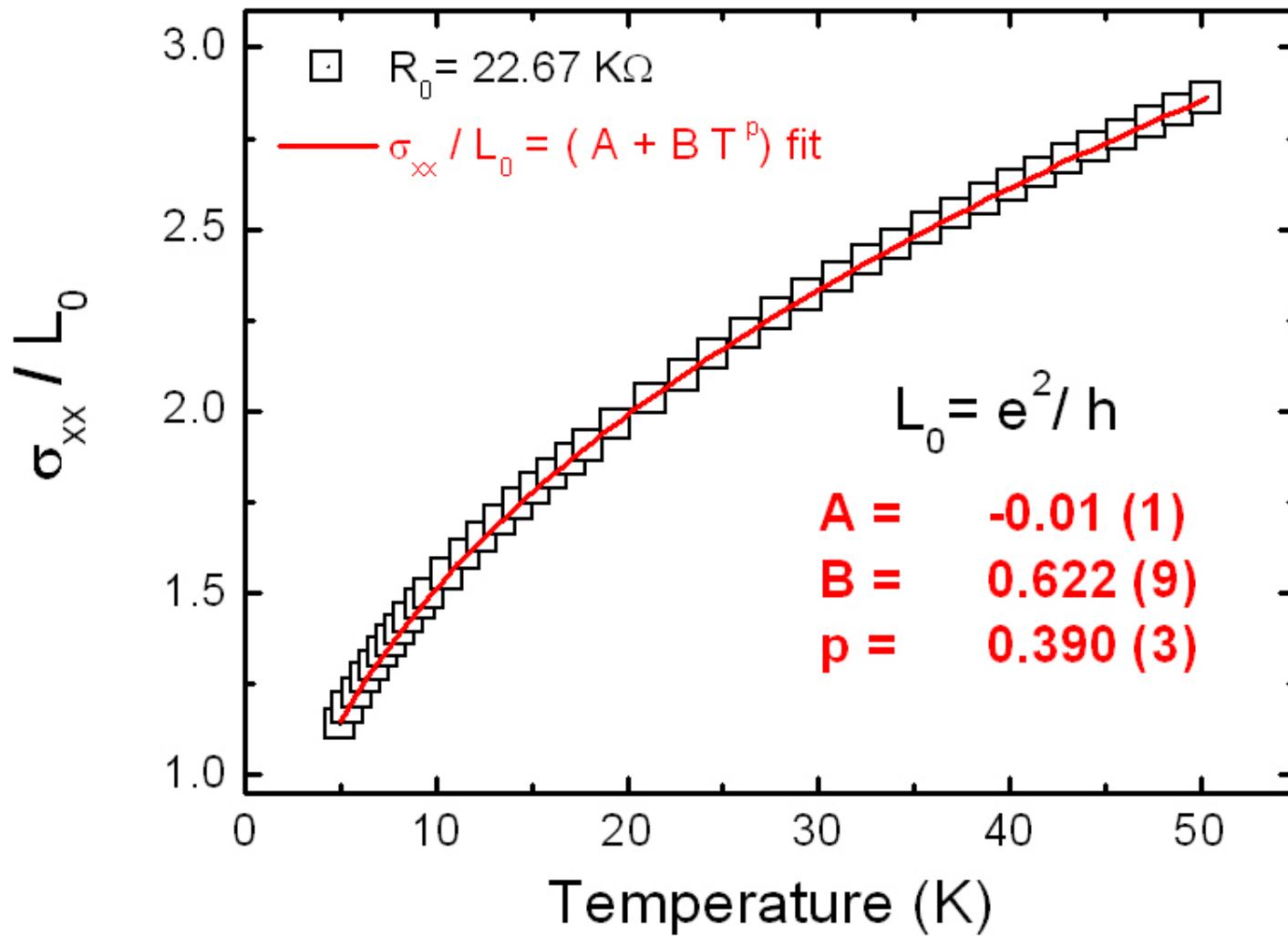


Conductivity is not a quantum correction & can be modeled as:

$$\frac{\sigma_{2D}}{(e^2/h)} = A + BT^p$$



Single sample closest to critical disorder ($A = 0$)

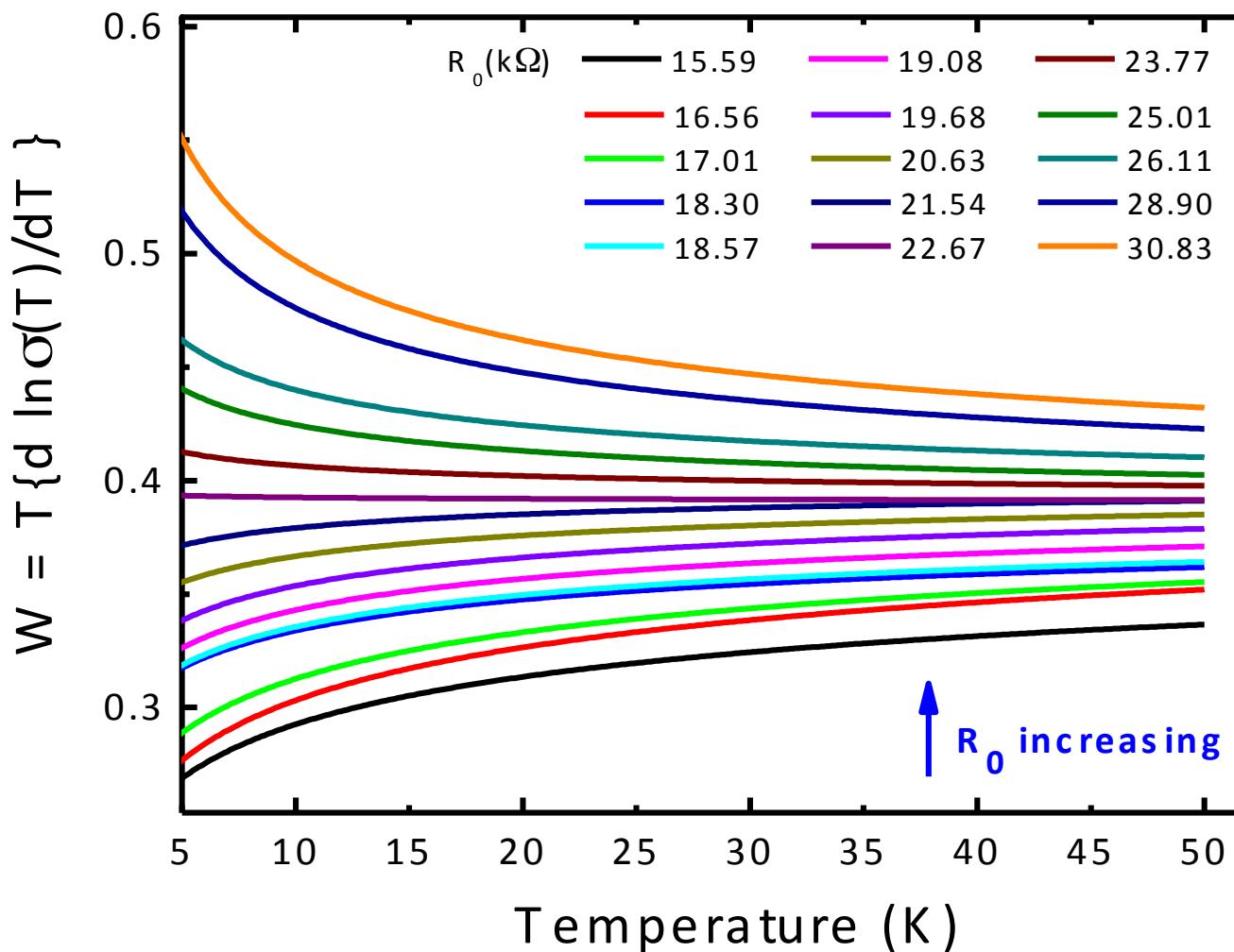


Remember $p = 0.390$ and $R_0 = R_c = 22.67 \text{ k}\Omega$!



Single film annealed: 16 stages

$w(T)$ plots: “normalized activation energy”



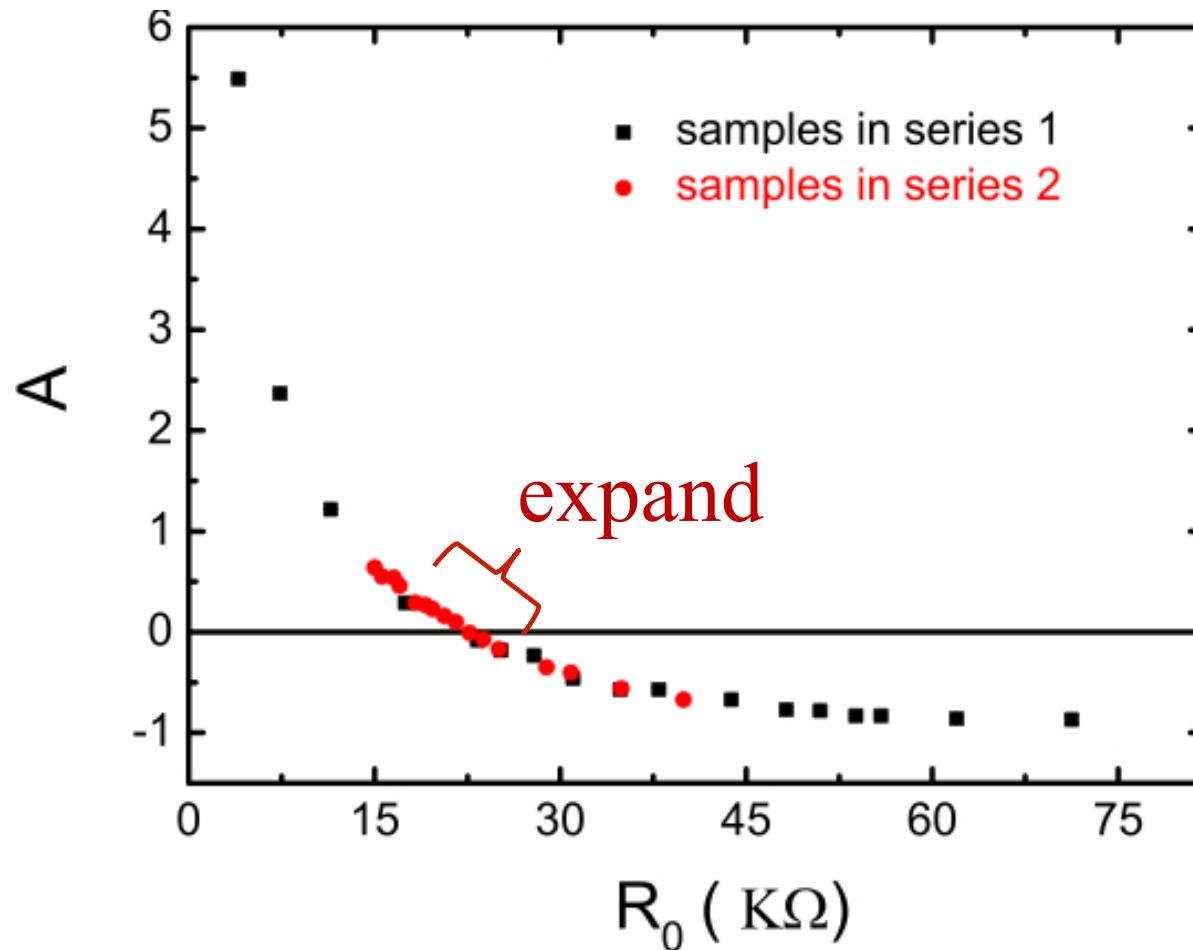
$$w(T) = \frac{d \ln(\sigma(T))}{d \ln(T)}$$

$$= \frac{d \ln(A + BT^p)}{d \ln T}$$

$$= \frac{pBT^p}{A + BT^p}$$



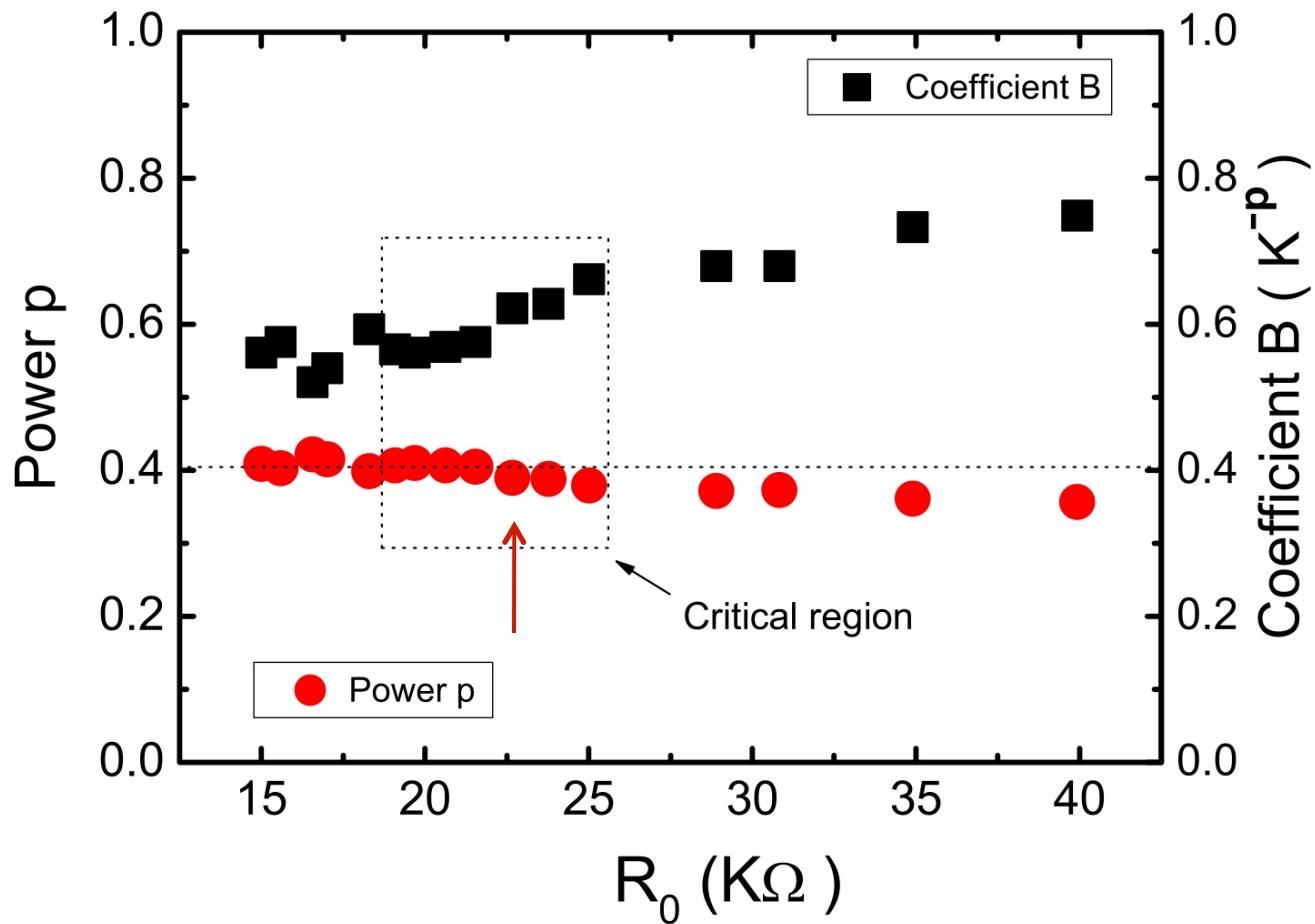
Parameter A as function of disorder



Series 1: 5 separate depositions with 2 samples undergoing 12 successive anneals.
Series 2: 1 sample undergoing 15 successive anneals.



Dependence of p & B on disorder



With $R_0 \uparrow$, $p \downarrow$ and $B \uparrow$

$$\frac{\sigma_{2D}}{(e^2/h)} = A + BT^p$$

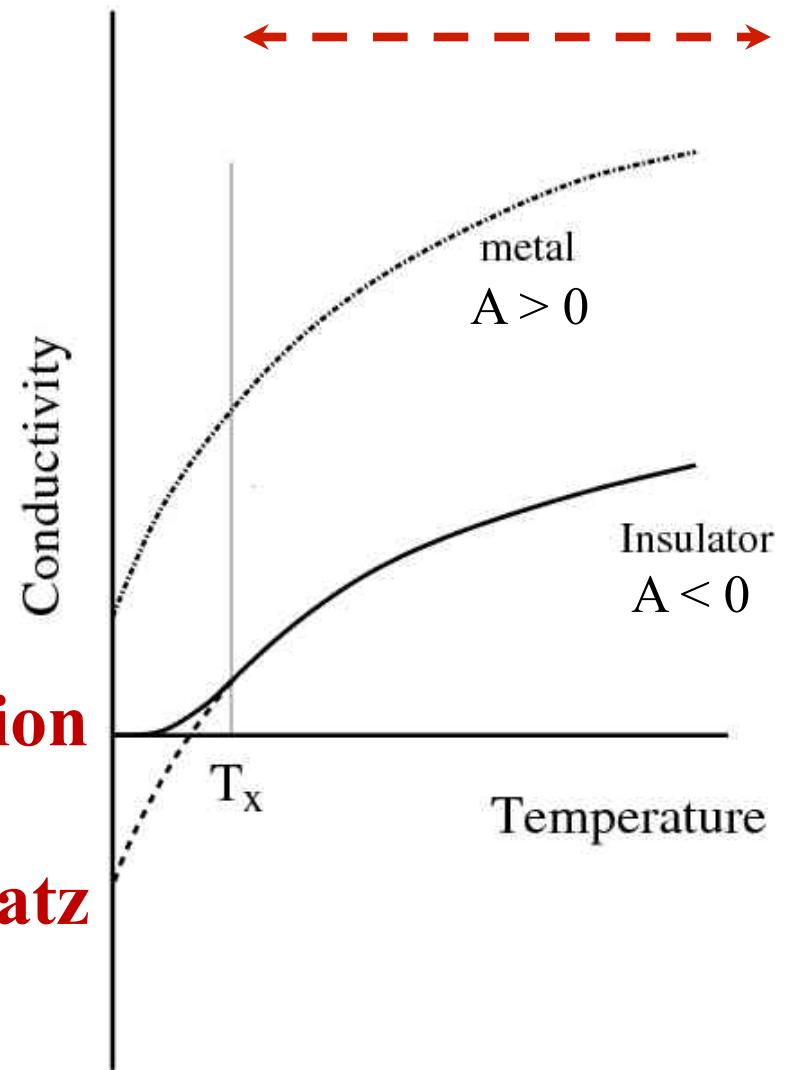


Negative conductivity ($A < 0$) at $T=0$?

Use finite temperature scaling
theory for $T > T_x$

$$\frac{\sigma_{2D}}{(e^2/h)} = A + BT^p$$

Note that the power-law description
is not a description of finite T
scaling but rather a heuristic anzatz
categorizing the data !





Primer on exponents: Finite T scaling of the Anderson QPT

$\sigma \sim (1 - \lambda / \lambda_c)^s$ dc conductivity, $\sigma(0)$, with exponent s

$\sigma(\omega; \lambda_c) \sim \omega^{1/z}$ dynamical conductivity, $\sigma(\omega)$, with exponent z

Replace frequency by $T \propto 1/\tau_\phi$, the phase relaxation rate

$\xi' \sim |1 - \lambda / \lambda_c|^{-\nu'}$ Correlation length (metal, $\lambda < \lambda_c$, $R_0 < R_c$)

$\xi \sim |1 - \lambda / \lambda_c|^{-\nu}$ Localization length (insulator, $\lambda > \lambda_c$, $R_0 > R_c$)

Exponents ν and ν' are not necessarily equal to each other !!!

In 3D, $\sigma \sim 1/\xi'$ & $s = \nu'$ (=1.6 by numerical calculations*) and $z = 3$

* K. Slevin and T. Ohtsuki, PRL 82, 382 (1999)



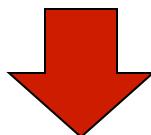
Finite temperature scaling description of the transition

σ near the transition given by the scaling form

$$\sigma(\omega; \lambda) = \xi^{-1} G(\pm 1, \xi \omega^{1/z}), \quad t > 0, t < 0$$

$\sigma(\omega) \propto \omega^{1/z} \propto T^{1/z}$ at critical point

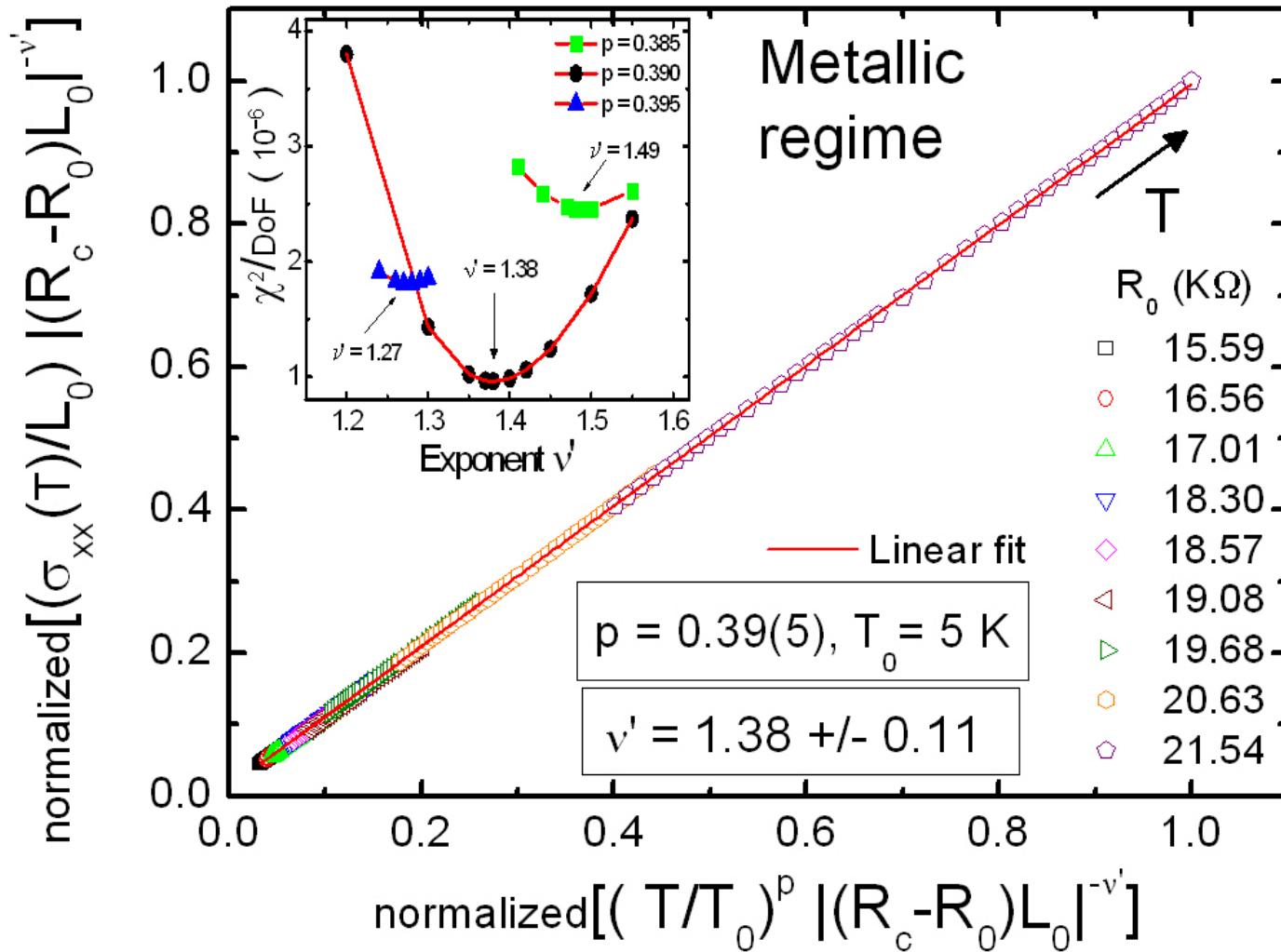
where $\xi \propto |R_0 - R_c|^{-\nu'} \rightarrow \infty$



$$|R_0 - R_c|^{-\nu'} \sigma(T; R_0) = G(\pm 1, |R_0 - R_c|^{-\nu'} T^{1/z})$$

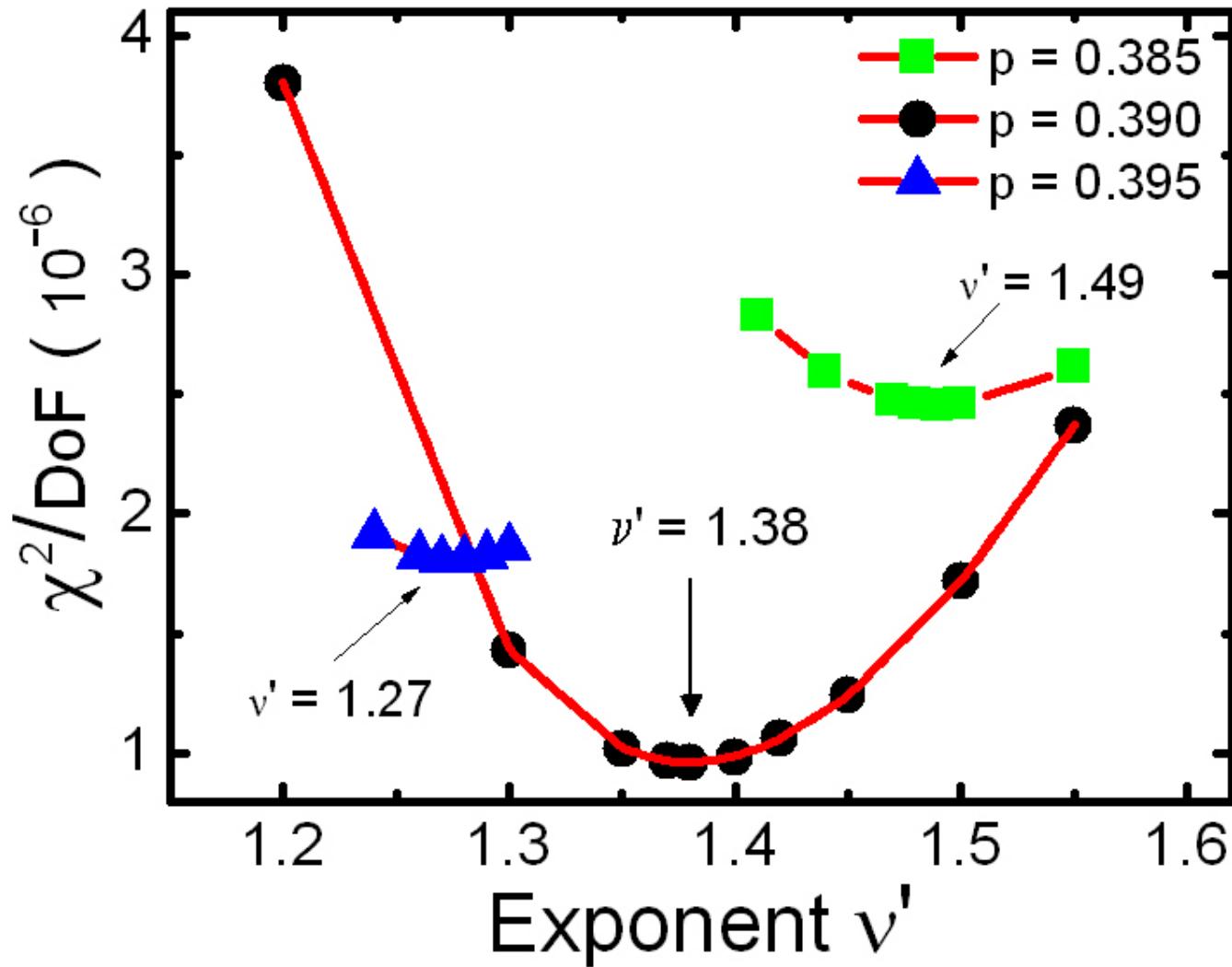


Scaling collapse for indicated values of R_0 (metallic side, recall $R_c=22.67 \text{ k}\Omega$)



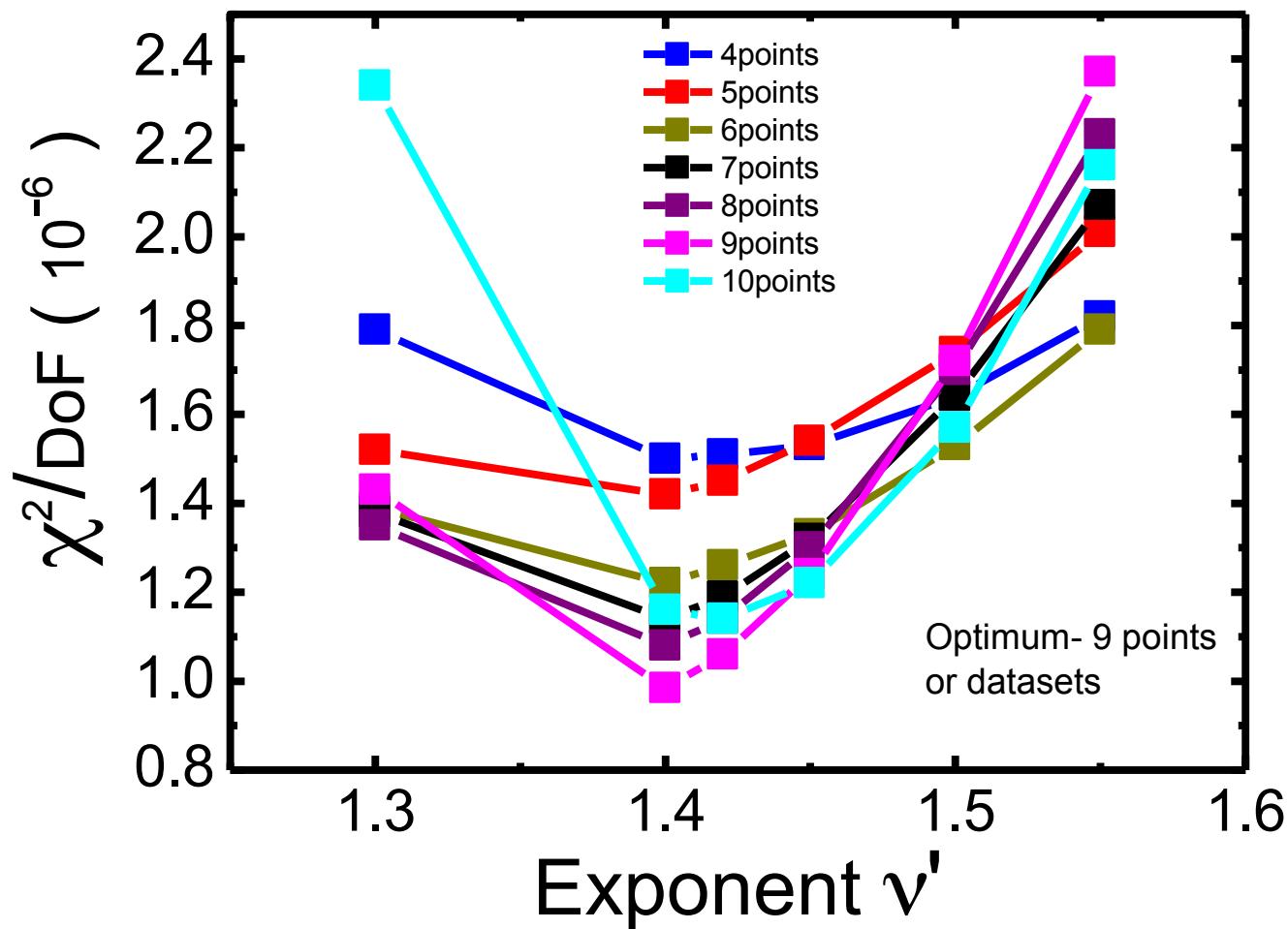


Sensitivity of ν' to power p at criticality (metal)





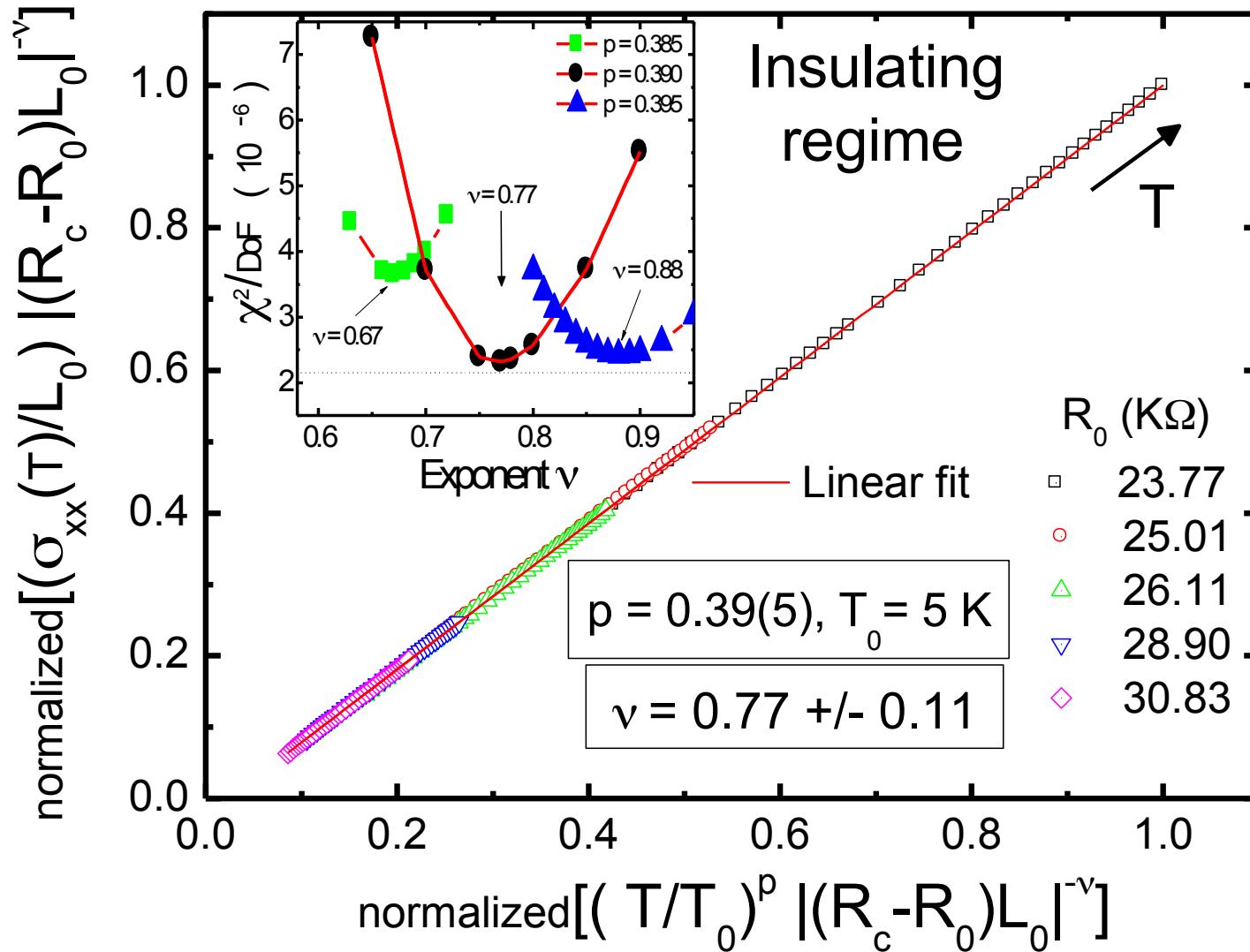
Dependence of χ^2 minima on # data sets (metallic side)



Optimum: include nine data sets on metallic side !

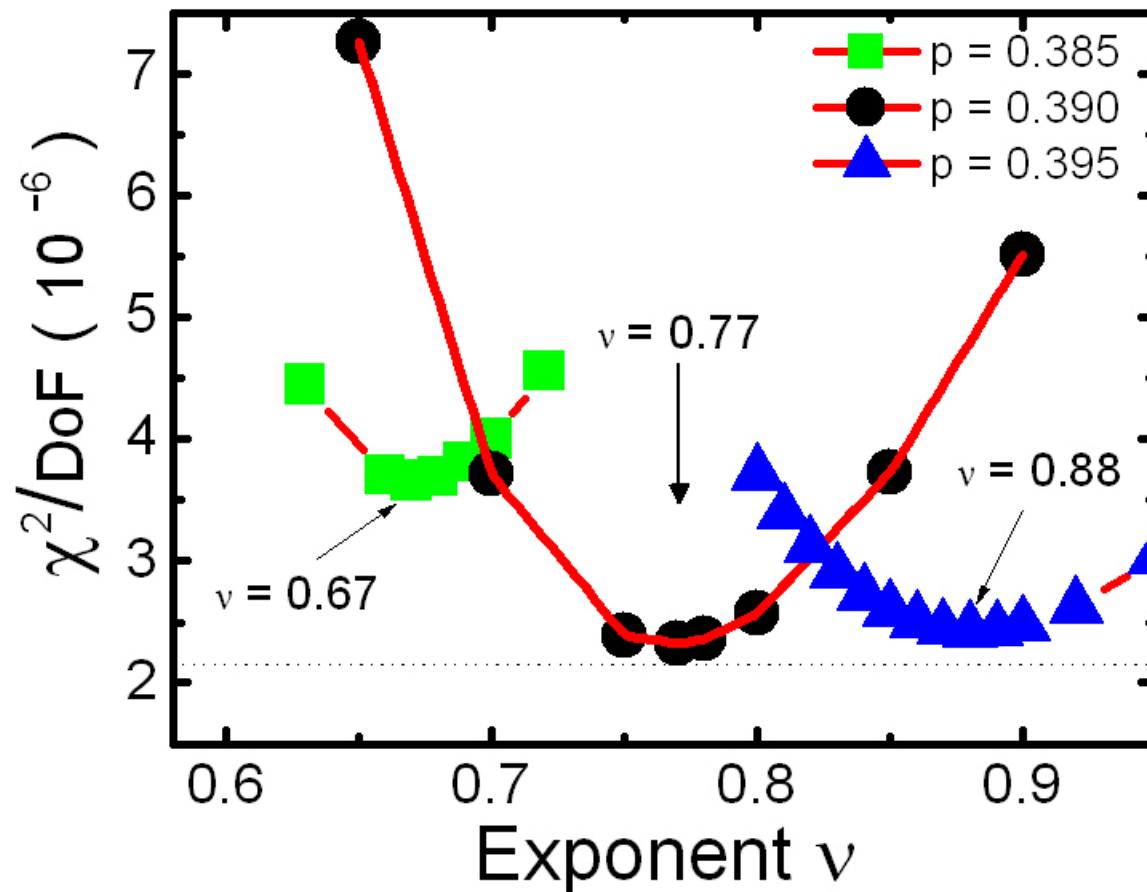


Scaling collapse for indicated values of R_0 (insulating side, recall $R_c=22.67 \text{ k}\Omega$)





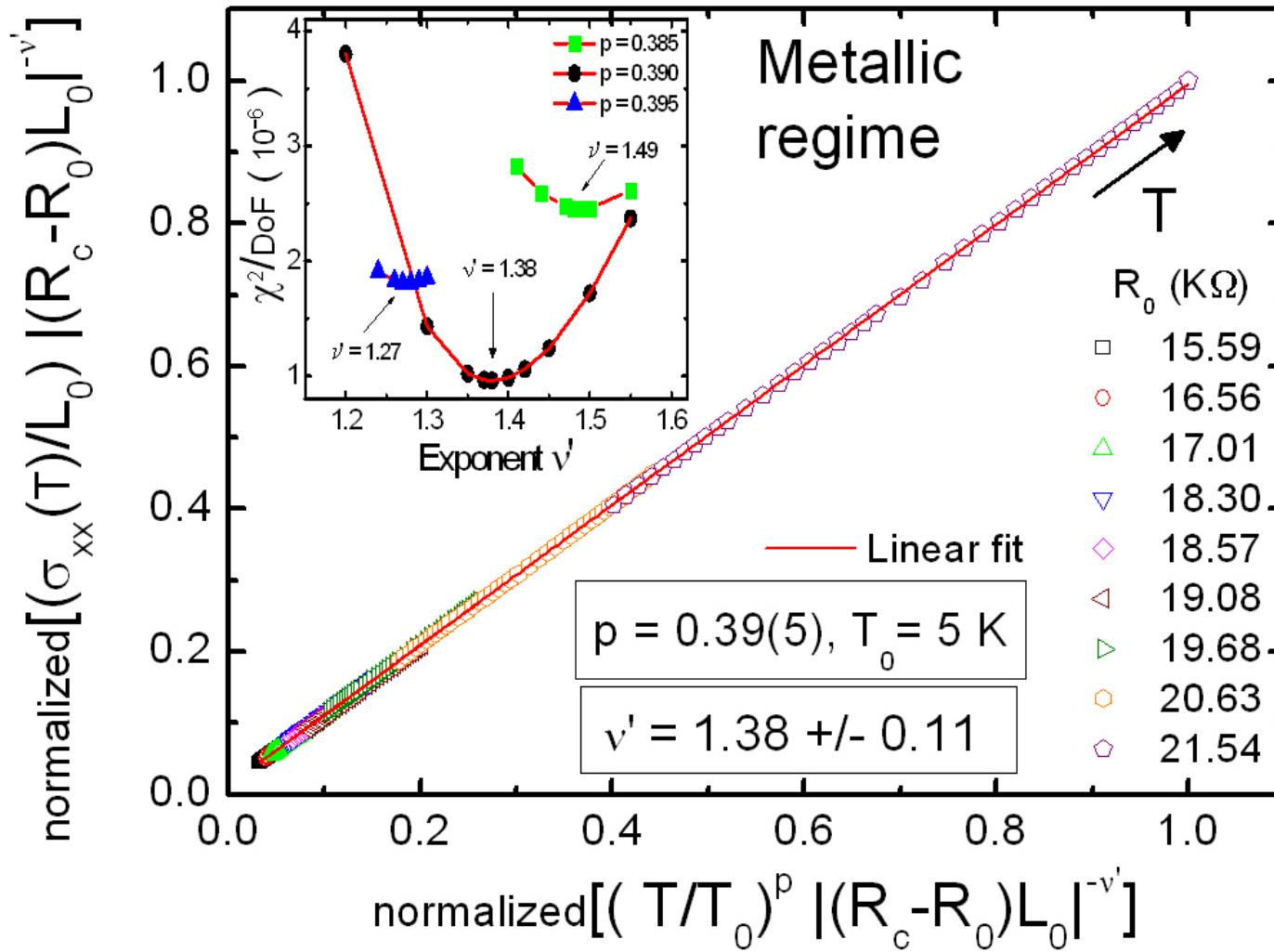
Sensitivity of ν to power p at criticality (insulator)



Substitute $\nu = \nu' = 1.38$ and χ^2 increases by 10 \times !

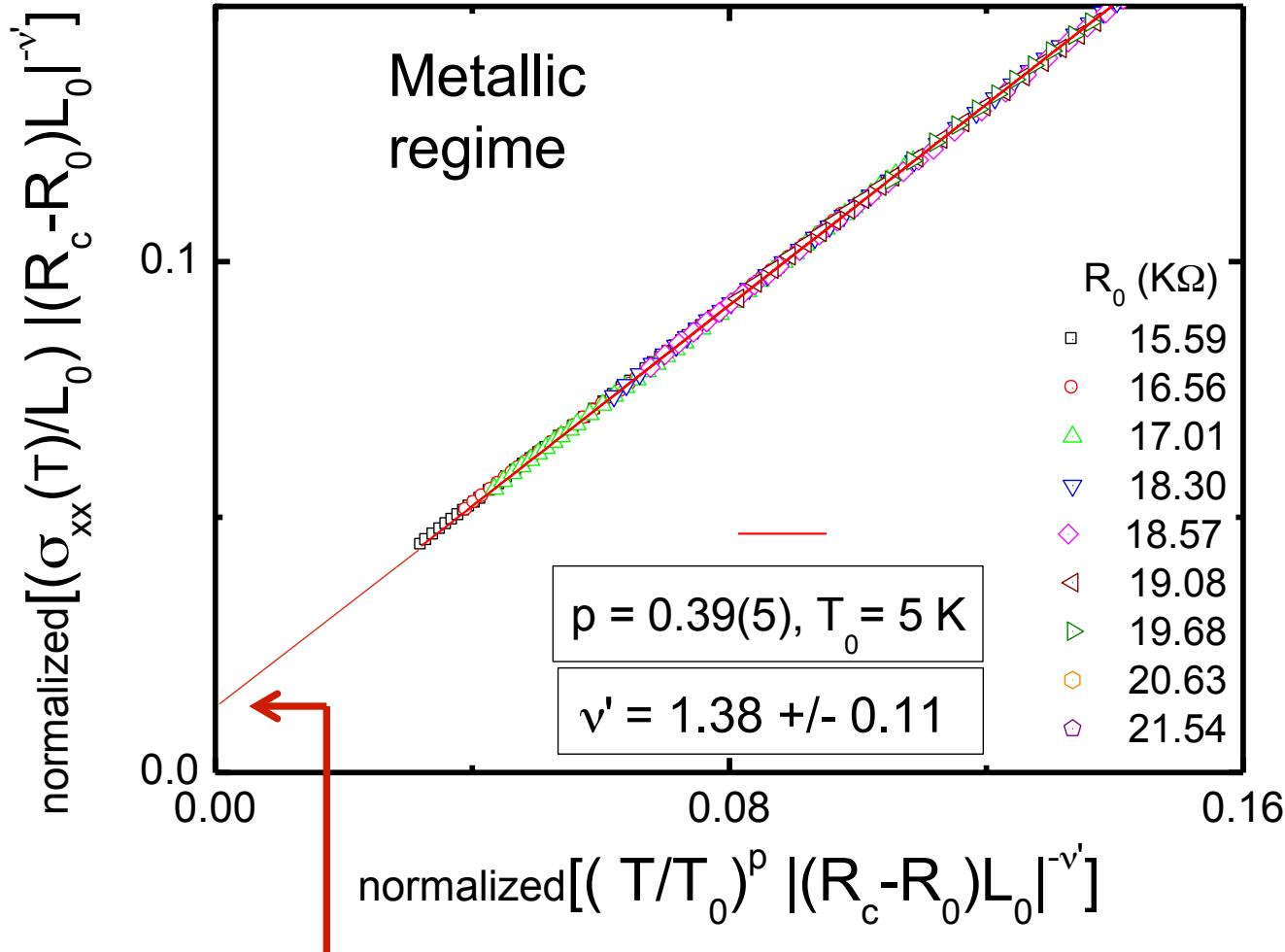


Scaling collapse for indicated values of R_0 (metallic side, recall $R_c=22.67 \text{ k}\Omega$)





Extrapolation to a non-zero intercept



The intercept a is independent of disorder strength !



Reconciliation with $w(T)$ plots

Recall our “first impression” with varying parameters

$$\sigma(T; R_0) / L_0 = BT^p + A$$

Linear scaling collapse tells us however that for the fixed coefficients B and $p = 1/z$ at criticality

$$\sigma(T; R_0) / L_0 = BT^{1/z} + a|R_0 - R_c|^{\nu'}$$

where a is the intercept of the collapsed data plot

dc conductivity exponent: $s = \nu' = 1.38$



Experiment is interpreted using finite T theory; $T=0$ extrapolations not needed!

At finite T in the scaling regime,

$$\omega > \omega_\xi = \frac{1}{\tau} (\xi/l)^{-3} \quad \text{or} \quad T > T_\xi$$

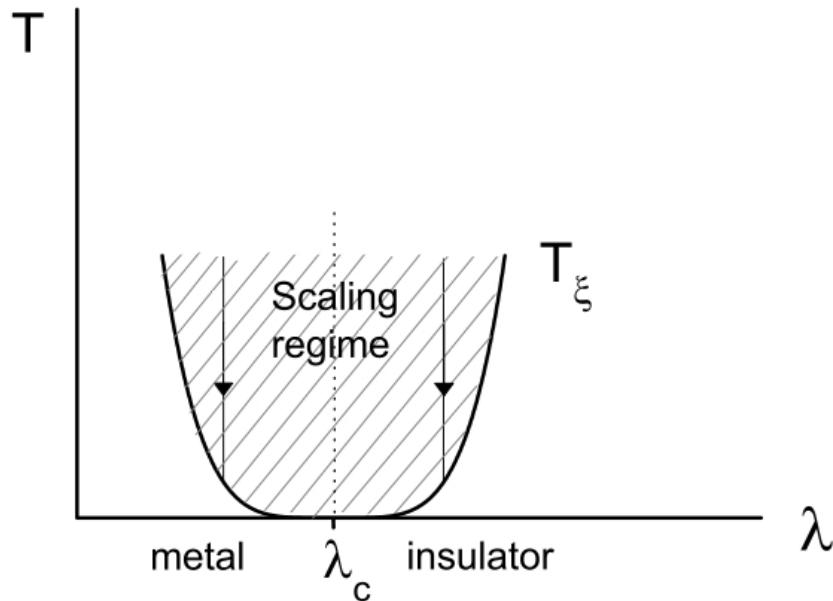
the d.c. conductivity is obtained from the dynamical conductivity, with leading dynamical scaling behavior

$$\sigma(\omega) \propto \omega^{1/3}$$

by replacing frequency by the phase relaxation rate $1/\tau_\varphi$

The effective dimension is **THREE**, provided the temperature dependent correlation length

$$L_\varphi < b, \quad (\text{b is the thickness of the film})$$



Magnetic Insulator

Local moment? Localized charge? FM, AFM, glass?
Lowest energy state? Spin waves? New phases?
Long range order? T_c ?

(I)

SAF state (dipole-dipole)
Anomalous Hall insulator



Emergent granularity

(II)

Emergent granularity

Power-law behavior &
M-I transition

Disorder strength (decreasing itinerancy)

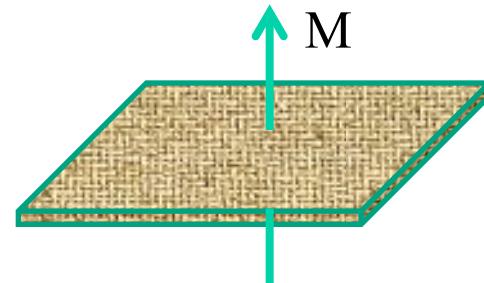
(III)



Curie temperature
(T_c) suppression

Quantum corrections to the conductivity in two dimensions

Polycrystalline magnetic thin films
(itinerant versus local moments)





Motivating Questions/(Answers)

1. Band ferromagnetism (FM) relies on itinerant electrons.
When itinerancy is compromised by disorder, what happens?
(FM is quite robust! Strong spin wave scattering is present!)
2. Any signatures at $\hbar/e^2 = 4100 \Omega$? (See only gradual crossovers.)
3. Is there a ferromagnetic-insulator transition? (Yes, asymmetric exponents, charge becomes localized but spin waves exist on both sides.)
4. Ferromagnetic behavior and film morphology? ($\sigma_{xy}^{SJM}/\sigma_{xy}^{SSM}$ is small (large) on glass (sapphire) substrates; granularity important for AHI; intergranular tunneling dominates longitudinal transport; Hall transport is controlled by intragranular scattering.)
5. Nonconventional magnetic insulators? (Yes)